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HYDRAULIC EXPERIMENTS WITH VALVES, ORIFICES, HOSE, NOZZLES, AND ORIFICE BUCKETS

BY
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VIRGIL R FLEMING, MELVIN L. ENGER

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ENGINEERING EXPERIMENT STATION

BULLETIN No. 105 MAY, 1918

HYDRAULIC EXPERIMENTS WITH VALVES, ORIFICES, HOSE, NOZZLES, AND ORIFICE BUCKETS

PART I

LOSS OF HYDRAULIC HEAD IN SMALL VALVES

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IN CHARGE OF THEORETICAL AND APPLIED MECHANICS

AND

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PART II

THE FLOW OF WATER THROUGH SUBMERGED ORIFICES

BY FRED B SEELY
ASSISTANT PROFESSOR OF THEORETICAL AND APPLIED MECHANICS

PART III

FIRE STREAMS FROM SMALL HOSE AND NOZZLES

BY VIRGIL R FLEMING
ASSISTANT PROFESSOR OF APPLIED MECHANICS

PART IV

THE ORIFICE BUCKET FOR MEASURING WATER

BY MELVIN L. ENGER
ASSOCIATE PROFESSOR OF MECHANICS AND HYDRAULICS

ENGINEERING EXPERIMENT STATION
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PREFACE

AS a part of the experimental work conducted in the Hydraulic Laboratory of the University of Illinois a number of problems has been investigated which has not been large enough in scope to warrant publication as separate bulletins. It seems well, however, to put on record the results of such experiments, and this bulletin presents a record of four of these problems. It is believed that the four papers will be found to be of use in various aspects of engineering practice even though the experiments are not exhaustive investigations.

The investigations for the most part have been the outgrowth of experimental work begun by students, largely as thesis work, and carried on over a period of several years.

The variety of conditions under which the flow of water takes place, the possibility of large changes in the state of the flow due apparently to small changes in the form of the passages through which the water flows, and the necessity of persistent effort in subjecting assumptions and analytical deductions to experimental verification, make it desirable to report all hydraulic experimental results which are believed to be reliable.

A part of the experimental results herein reported has appeared in the publication of a technical society. The material, however, has been expanded in this bulletin and will be found in a more convenient form for use.

ARTHUR N. TALBOT
FRED B SEELY
Editors

Part I

LOSS OF HYDRAULIC HEAD IN SMALL VALVES

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AND

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HYDRAULIC EXPERIMENTS

WITH

VALVES, ORIFICES, HOSE, NOZZLES, AND ORIFICE BUCKETS

Part I

LOSS OF HYDRAULIC HEAD IN SMALL VALVES

I. Introduction

1. *Preliminary.*—Part I of this bulletin presents the results of experiments on the flow of water through 1-in. and 2-in. gate valves, 1-in. and 2-in. globe valves, and 1-in. and 2-in. angle valves. The loss of head caused by each valve, expressed in terms of the velocity head in the pipe, is given for four different ratios of the height of the valve opening to the diameter of the full valve orifice, namely, ¼, ½, ¾, and 1. The coefficients of discharge are also given for the gate valves for each of the four valve openings.

In a long pipe line the total amount of lost head is caused chiefly by pipe friction, the resistance due to a valve being comparatively small except for very small valve openings.

In a variety of cases, however, where valves are used on comparatively short pipe lines as, for example, in hydraulic elevator service, in office buildings, and in special apparatus it is important to know the lost head caused by small valves of different kinds when set at various positions. Very few experimental results have been published on this subject, particularly for globe and angle valves. Any experimental work, furthermore, which helps to indicate the laws governing the flow of water should prove of value. With these facts in mind the results herein recorded have been prepared.

2. *Acknowledgment.*—The experiments herein considered were performed as student thesis work in the Hydraulic Laboratory of the University of Illinois by M. E. Thomas, class of 1906, under the direction of Professor Arthur N. Talbot. Unusual care in the experimenting is reflected in the congruity of the data presented in Mr. Thomas' thesis.

II. Apparatus and Method of Experimenting

3. *Valves.*—The valves used were bought in the open market and tested just as received. The passages through the 2-in. globe valve were then modified by the use of plaster of paris to give a more gradual change of section (see Fig. 10), and this valve was tested again. The types or forms of the interiors of the valves and the dimensions of some of the passageways through the valves are shown in Fig. 1. The 1-in. globe valve and the 1-in. angle valve were made by the Western Tube Company. All the other valves were made by the Crane Company.

4. *Method of Experimenting.*—The arrangement of the apparatus is shown in Fig. 2. The test valve was placed in a horizontal pipe to which water was supplied from a standpipe under a static head of about 50 feet. The quantity of water discharged through the valve was regulated by another valve downstream from the test valve. The volume discharged in a certain time was measured in a calibrated pit and the time taken with an ordinary watch from which the rate of discharge was calculated. Three-way gage connections for obtaining the pressure head in the pipe were made at a section one foot upstream and one foot downstream from the valve. Care was taken to avoid having these connections project into the interior of the pipe. It was found by experiment that when any two of the three pressure connections at either section were closed, the same difference of head was registered as when all three connections at either section were open. The three-way connections were used, however, in all the experiments. The difference in the pressure heads at the two sections was measured by a differential mercury gage. A Crosby pressure gage was also attached at each section to serve as a rough check on the differential gage. The lost head due to the pipe friction for the two feet of pipe between the two sections was assumed to be as given in Weston's Tables of Friction of Water in Pipes. This amount of lost head was subtracted from the reading of the differential mercury gage in determining the loss of head caused by the valve.

The loss of head and the corresponding rate of discharge and velocity in the pipe were determined for each of four valve openings for each of the six valves tested. The valve openings used were such that the heights of the openings were one-fourth, one-half, three-fourths, and one times the diameter of the full valve orifice.

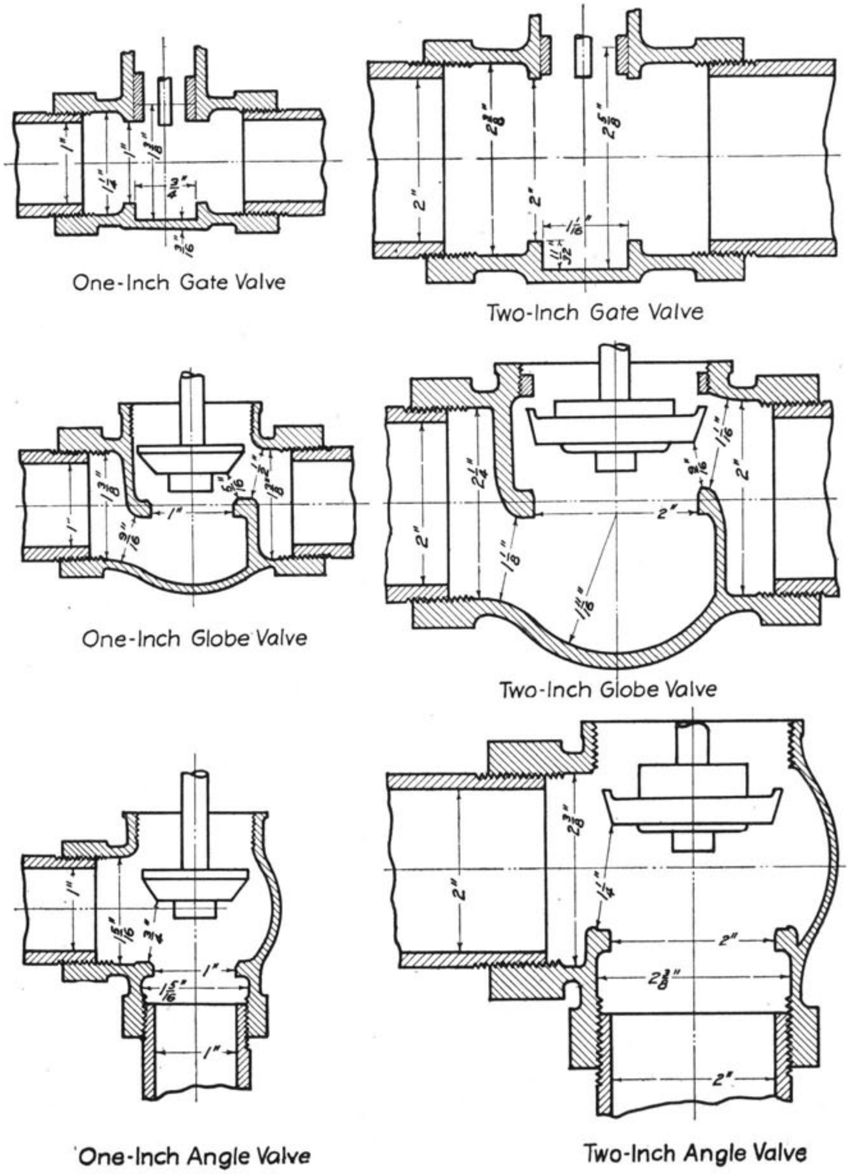

FIG. 1. LONGITUDINAL SECTIONS OF VALVES TESTED

III. Experimental Results and Discussion

5. *Loss of Head.*—In Fig. 3 to 8 values of the lost head caused by the valve are plotted as abscissas and the mean velocity in the pipe as ordinates. The assumed value of the friction head for the two feet of pipe between pressure connections is subtracted from the differential mercury gage reading in plotting the abscissas. There is, of course, some doubt concerning the correct allowance to be made for this pipe friction. The loss of head due to this cause, however, will be relatively small except for the larger valve openings. It will be noted from the curves in Fig. 3 to 8 that the range of velocity in the pipe varied of course with the kind of valve and with the amount of valve opening. The smallest mean velocity in any case was about ¼ ft. per sec., while the maximum mean velocity was about 40 ft. per sec.

The curves in Fig. 3 to 8 give values of the loss of head caused by the valves which vary as the square of the velocity in the pipe, that is, the lost head due to the valve may be expressed in terms of the velocity head in the pipe. This fact is shown very clearly by plotting the values from the curves in Fig. 3 to 8 on logarithmic paper; the curves showing the relation between the lost head, h, and the velocity in the pipe, v, become parallel straight lines with a slope varying but little from two, the slope indicating the exponent in the equation $h=kv^n$. That is, $h=kv^2$ or, when expressed in terms of the velocity head in the pipe, $h=\frac{mv^2}{2g}$ in which m is called the coefficient of loss.

Values of the coefficients of loss for the valves with the various valve openings as obtained from the curves in Fig. 3 to 8 are given in Table 1. These values have been plotted in Fig. 9 as abscissas against the valve openings as ordinates. From these curves and also from Table 1 the resistance to flow caused by the three kinds of valves may be compared at various valve openings. It will be noted that the loss of head varies in a quite different manner with the amount of valve opening for these three kinds of valves, for instance, a comparison of the results for the valves when completely opened shows that a globe valve causes more than twice as much loss of head as the corresponding size of angle valve, while a gate valve causes markedly less loss than either a globe or an angle valve, the velocity in the pipe being the same in the three cases. As the valve is gradually closed, the resistance to flow of the angle valves increases the least (decreasing at first) while the resistance

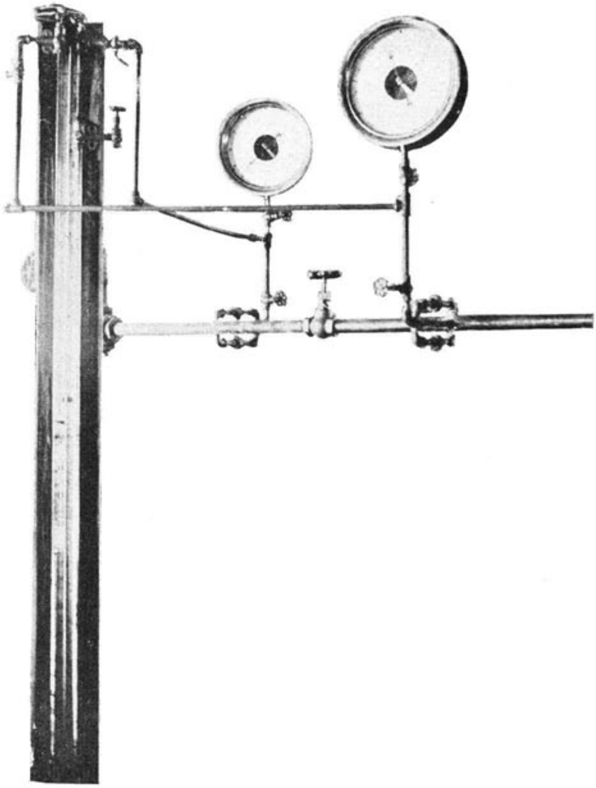

Fig. 2. Arrangement of Apparatus

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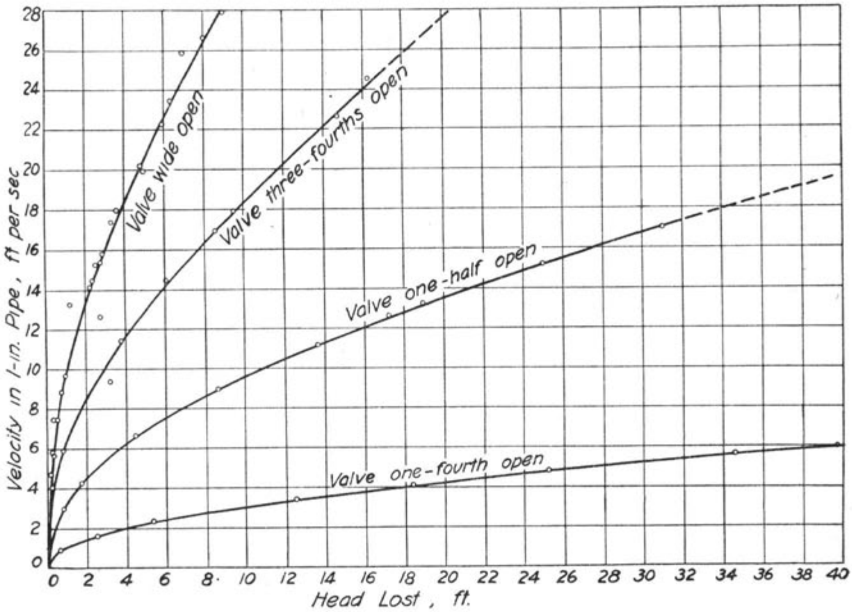

FIG. 3. CURVES SHOWING THE RELATION BETWEEN THE VELOCITY AND HEAD LOST IN 1-INCH GATE VALVE

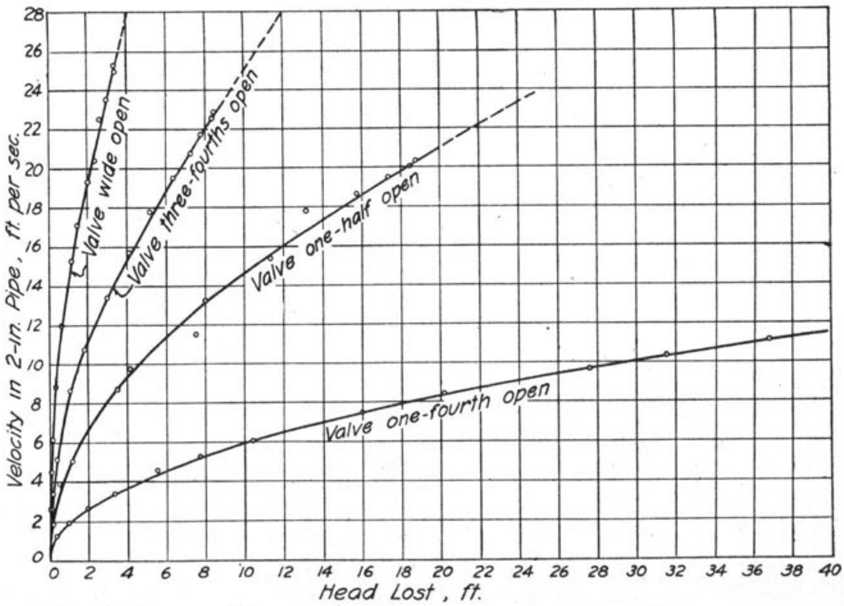

FIG. 4. CURVES SHOWING THE RELATION BETWEEN THE VELOCITY AND HEAD LOST IN 2-INCH GATE VALVE

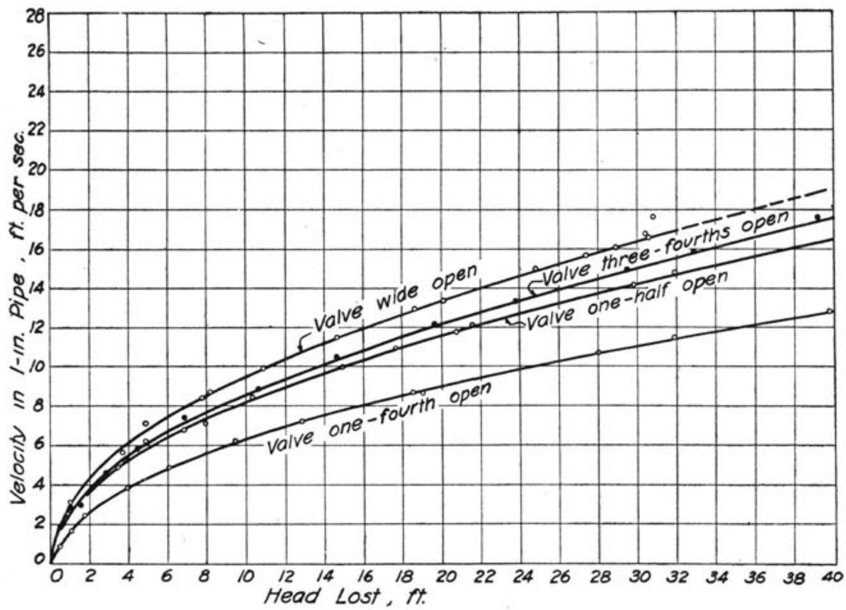

FIG. 5. CURVES SHOWING THE RELATION BETWEEN THE VELOCITY AND HEAD LOST IN 1-INCH GLOBE VALVE

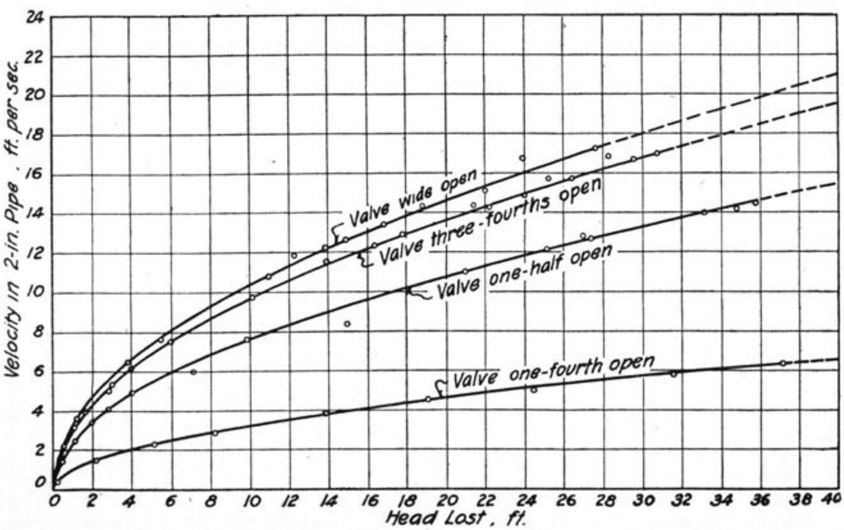

FIG. 6. CURVES SHOWING THE RELATION BETWEEN THE VELOCITY AND HEAD LOST IN 2-INCH GLOBE VALVE

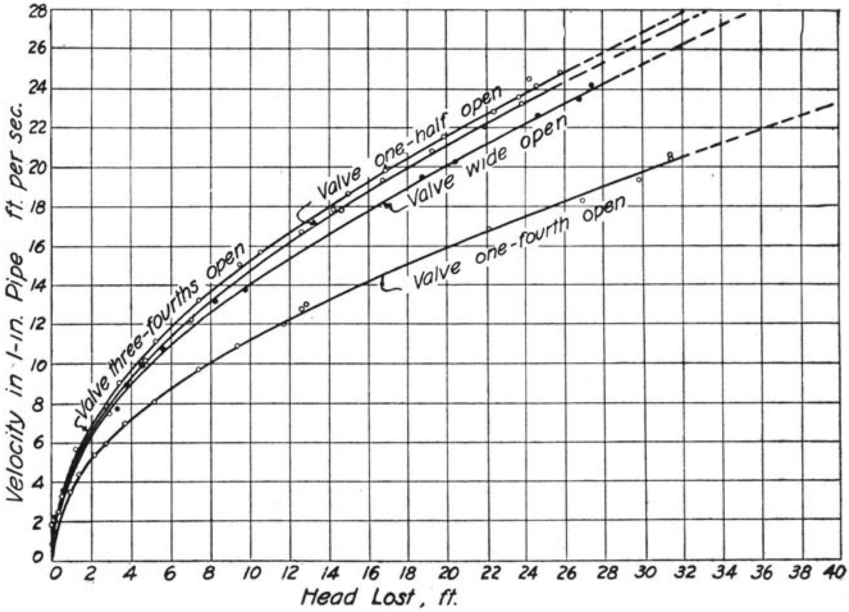

FIG. 7. CURVES SHOWING THE RELATION BETWEEN THE VELOCITY AND HEAD LOST IN 1-INCH ANGLE VALVE

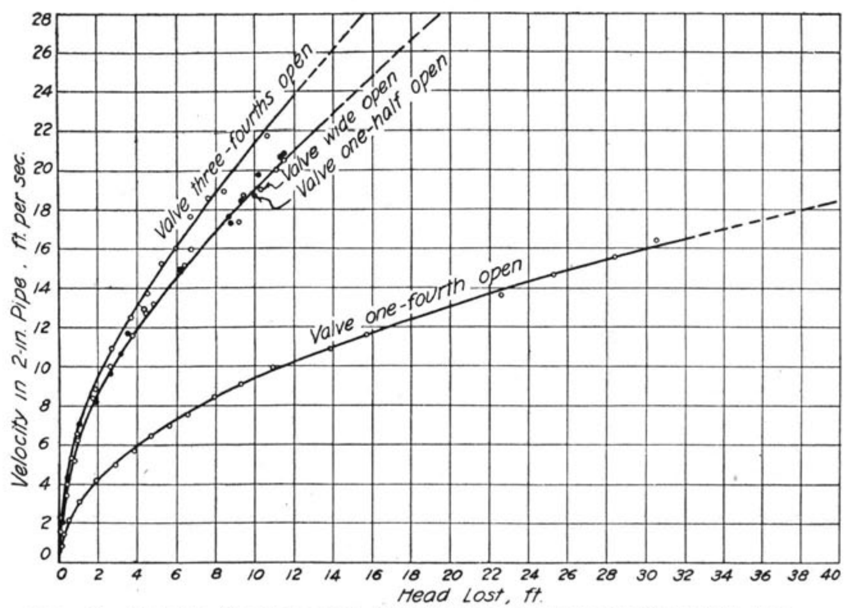

FIG. 8. CURVES SHOWING THE RELATION BETWEEN THE VELOCITY AND HEAD LOST IN 2-INCH ANGLE VALVE

of the gate valves increases the most rapidly, although the rate of increase in any case is comparatively small until the valve is at least one-half closed.

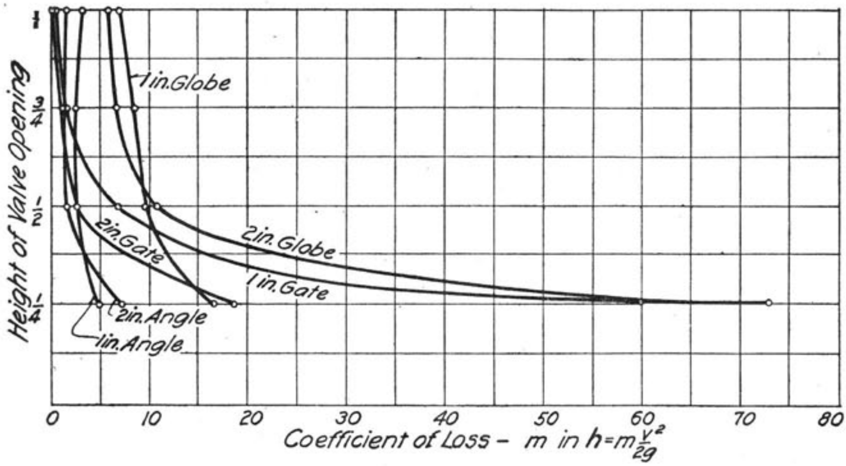

FIG. 9. CURVES SHOWING THE RELATION BETWEEN COEFFICIENTS OF LOSS AND VALVE OPENINGS

Fig. 9 also indicates that the proportions or form or shape of the passageways of the valve of a given type or kind is a very important factor in causing loss of head. This fact is shown by a comparison of the results for the 1-in. globe valve with those for the 2-in. globe valve and also by a comparison of the results of the 1-in. angle valve with those of the 2-in. angle valve. Each of these 1-in. valves was of a somewhat different form from that of the corresponding 2-in. valve as may be seen in Fig. 1. It will be noted from Fig. 9 and Table 1 that

TABLE 1

EXPERIMENTAL VALUES OF COEFFICIENTS OF LOSS

Values of m in $h = \frac{mv^2}{2g}$

Ratio of Height of Valve-Opening to Diameter of Full Valve Opening	Gate Valves		Globe Valves		Angle Valves	
	1-inch Diameter	2-inch Diameter	1-inch Diameter	2-inch Diameter	1-inch Diameter	2-inch Diameter
¼	73.0	18.8	16.6	60.0	5.00	7.3
½	7.0	2.94	9.62	10.9	2.90	1.70
¾	1.84	1.06	8.75	6.84	2.72	1.44
1	0.74	0.35	7.12	6.0	3.23	1.70

for the smaller valve openings the 1-in. globe valve and the 1-in. angle valve cause less resistance to flow than the corresponding 2-in. valves. The difference is especially large in the case of the globe valves. This unexpected result seems to be due chiefly to the better shaped discharge passages (more gradual expansion) as the water makes its exit from the 1-in. globe valve.

Experiments were made on the 2-in. globe valve to see if a more gradual change in sections through the valve would cause less loss of head. This gradual change was made by filling in part of the passageway with plaster of paris, as shown in Fig. 10. This modified valve was then tested with the valve one-half open and wide open, the results for which are shown in Fig. 10. It will be seen that this modification had no

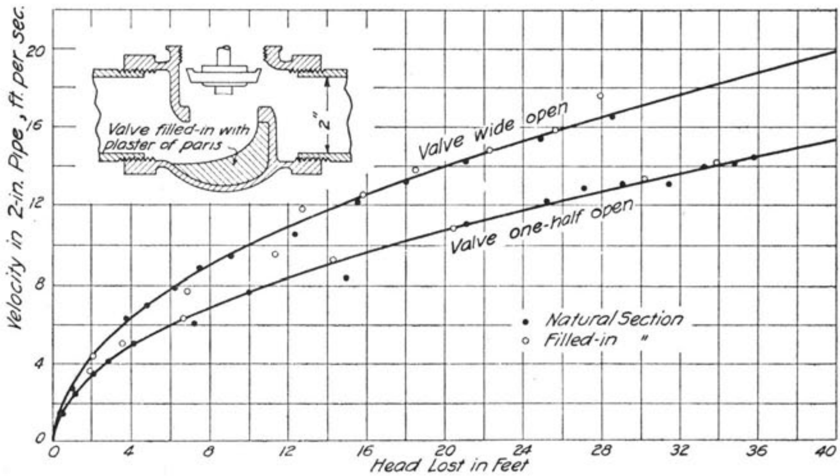

FIG. 10. CURVES SHOWING THE EFFECT OF GRADUAL CHANGE OF SECTION THROUGH 2-INCH GLOBE VALVE

effect on the amount of head lost. This suggests that the lost head in a small globe valve is caused more by the form or shape of the passageway at exit from the valve than by the form of the passages through the valve. Other valve openings and other modifications of the passageways, however, may give better results.

In the case of angle valves the loss of head is not a minimum for the greatest valve opening as is shown in Table 1 and in Fig. 9. For the 2-in. angle valve the lost head is the same when the valve is only one-half open as it is when the valve is wide open, the velocity in the pipe for the two valve openings being the same, that is, the coefficient of loss is the same for these two valve openings. When this valve is three-fourths open, however, the coefficient of loss is about 20 per cent less than when the valve is one-half open or wide open. The 1-in. globe valve caused a smaller amount of lost head when it was one-half and three-fourths open than it did when wide open, the velocity in the pipe being the same for each of the valve settings. The difference, however, between the coefficients of loss for these three valve openings is not large. The reason that the minimum loss of head in the angle valves occurs when the valve is about three-fourths open is probably because at this opening the water can flow through comparatively large openings all around the valve disc meeting with less abrupt changes of directions than when the valve is wide open. In the latter case there is much turbulent action due to the impact of the water against the bottom of the valve. As the valve opening decreases from the three-fourths open position, the greater resistance due to the narrowing passages causes the lost head to increase again.

The assumption is sometimes made that for comparatively small valves of like type or kind the loss of head varies inversely with the diameter of the valve. For the larger valve openings this assumption is probably approximately true, but from the foregoing results and discussion it would seem that at least for globe and angle valves the form or shape of the passages of the valve is a determining factor in the amount of head lost at the smaller valve openings.

6. *Earlier Experiments on Gate Valves.*—Among the first reliable published results on valves were those by Weisbach.* The largest gate valve used by Weisbach was a little less than two inches. Globe and angle valves, at least of modern construction, were not tested. Other experiments on gate valves have been reported by Magruder† on ⅜-in., ½-in., ¾-in., 1-in., and 1½-in. gate valves, by Folwell‡ on a 4-in. gate valve, by Kuichling¶ on a 24-in. gate valve, and by J. Waldo Smith§ on a 30-in. gate valve. In Smith's experiments the 30-in. valve was located in a 42-in. pipe with increaser-shaped or Venturi-shaped approaches, and in Kuichling's experiments the valve was placed in one branch of a Y only a few feet from the section where the Y started to branch. The methods of determining the lost head in the

* Mechanics of Engineering (Coxe's translation).
† Engineering Record, Vol. XL, p. 78, 1899.
‡ Engineering News, Vol. XLVII, p. 302, 1902.
¶ Trans. Am. Soc. Civ. Eng. Vol. XXVI, p. 439, and Vol. XXXIV.
§ Trans. Am. Soc. Civ. Eng. Vol. XXXIV, p. 235 (p. 243), 1895.

various experiments were also different. For these reasons it is obvious that the results of these experiments are not directly comparable.

TABLE 2

VALUES OF THE COEFFICIENT OF LOSS FOR GATE VALVES OF VARIOUS DIAMETERS DUE TO PARTIAL CLOSURE ONLY

Ratio of Height of Opening to Diameter of Full Valve Orifice	Weisbach	Kuichling	Smith	Folwell		This Bulletin	
	2½-inch Diameter	24-inch Diameter	30-inch Diameter	4-inch Diameter		2-inch and 1-inch	
	Parallel Sides	Parallel Sides	Parallel Sides Venturi-Shaped Approaches	Parallel Sides	Wedge Shaped	Parallel Sides	
						2-inch Diameter	1-inch Diameter
0	......	......	......	......	......	......	......
3/100	......	......	950.0	......	......	......	......
1/10	......	......	128.0	......	......	......	......
⅛	98.0	......	90.0	72.3	104	......	......
¼	17.0	22.7	17.0	16.8	20.5	18.45	72.3
⅜	5.5	8.63	7.5	6.19	8.0	7.0[1]	16.0[1]
½	2.1	3.27	3.5	2.58	2.72	2.59	6.26
⅝	0.81	1.09[1]	1.5	1.22	1.5	1.2[1]	2.5[1]
¾	0.26	0.25	0.50	0.55	0.66	0.71	1.10
⅞	0.07	0.019	0.19	0.20	0.16	0.15[1]	0.70[1]
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00

[1] Interpolated from curve.

In Table 2 are given the values of the coefficients of loss as obtained by the various experimenters mentioned previously, as well as the values obtained in the experiments herein reported. These values of the coefficients of loss are those due to partial closure of the valves only, that is, in excess of the loss of head caused by the valve when wide open. Smith's experiments are the only ones in which valve openings less than one-eighth were used. There is considerable chance for error in the results obtained for the very small valve openings, due chiefly to the uncertainty in securing the valve setting desired. Table 2 indicates a rather close agreement in the coefficient of loss for all the gate valves having diameters of 2 in. or greater, and for valve openings of ¼ or perhaps ⅛ and greater. The values for the 1-in. valve show a considerable increase in the lost head over that for valves of 2-in. diameter and greater. It is probable also that there is considerable variation in the smaller valves of any one type and size.

7. *Coefficients of Discharge for Gate Valves.*—In order to determine the rate of discharge through a pipe a partially closed valve has sometimes been used. This requires the values of the coefficients of discharge of the valve for various valve openings since the rate of discharge, q, is found from the expression, $cA\sqrt{2gh}$, in which c is the coefficient of discharge, A the area of the valve opening, and h the difference in pressure heads on the two sides of the valve (lost head), velocity of approach being neglected. The average values of the coefficients of discharge for the 1-in. and 2-in. gate valves as found in the experiments reported in this bulletin are given in Table 3. The value of the

TABLE 3

EXPERIMENTAL VALUES OF THE COEFFICIENTS OF DISCHARGE FOR GATE VALVES

Values of $c = \dfrac{q}{A\sqrt{2gh}}$

Ratio of Height of Valve-Opening to Diameter of Full Valve-Opening	Coefficient of Discharge		Area of Valve-Opening Square Inch	
	1-inch Valve	2-inch Valve	1-inch Valve	2-inch Valve
¼	.48	.88	.195	.826
½	.67	1.00	.450	1.80
¾	.88	1.12	.660	2.67
1	1.16	1.70	.785	3.14

coefficient varied somewhat with the velocity for any given valve opening. Because of the uncertainty of obtaining the exact valve setting desired and the corresponding uncertainty in the area of the valve opening, the values of the coefficients of discharge given in Table 3 cannot be considered as refined determinations.

It will be noted that the coefficient of discharge increases directly with the valve opening for each of the gate valves for a range of valve openings of ¼ to ¾ or perhaps greater. The more the valve is opened the greater is the velocity of approach toward the valve and since the velocity of approach is not considered in the calculation of the coefficient of discharge the value of the coefficient increases with the valve opening. The coefficient of discharge for the valves used by Kuichling and Smith decreased slightly until the valve was about one-fourth open and then increased rapidly for further openings of the valve. Gibson with a 2½-in. flat disc stop valve found nearly a constant coefficient of discharge of 0.80. These variations in the coefficients of discharge are not surprising considering the wide range of conditions covered by the experiments. They suggest, however, that if gate valves are to be used for determining the rate of discharge in pipes with reasonable accuracy much more experimenting is required, or better, where it is possible, experiments should be performed under service conditions to calibrate the particular valve to be used.

8. *Summary.*—The following brief summary is given as applying to 1-in. and 2-in. valves of the three kinds tested (gate valves, globe valves, and angle valves) with valve settings ranging from one-fourth open to wide open.

(1) The loss of head caused by small valves varies as the square of the velocity in the pipe for all the valve openings; hence the lost head may be expressed as a constant times the velocity head in the pipe, $\left(h=\frac{mv^2}{2g}\right)$.

(2) When wide open a globe valve causes more than twice as much loss of head as an angle valve of the same size, while a gate valve causes much less loss of head than either a globe or an angle valve, the velocity in the pipe being the same in the three cases.

(3) The loss of head for an angle valve is somewhat less when about three-fourths open than when wide open, the velocity in the pipe being the same in each case.

(4) The loss of head for each valve, as the valve is closed from a wide open position, varies comparatively little with the valve opening until the valve is at least one-half closed. As further closure takes place the loss of head of the globe valves and gate valves increases rapidly and is considerably larger than that of the angle valves.

(5) The form or shape of the passageways through a globe or angle valve has a large influence on the loss of head for the small

valve openings. The portion of the passageways in which the form seems of greatest importance is in the exit from the valve rather than in the passageways leading to the valve disc or seat. On account of the influence of the form or shape of the valve no law giving the relation of the lost head to the diameter of the valve can be stated for valve settings less than five-eighths open. For larger valve openings than this, the lost head seems to vary approximately inversely as the diameter.

(6) The use of the lost head through a partially closed valve as a means of determining the flow can be only a very rough method of measurement unless the particular valve to be used is calibrated under service conditions. Even then the difficulty in obtaining the desired valve setting may introduce considerable uncertainty in the results.

PART II

THE FLOW OF WATER THROUGH SUBMERGED ORIFICES

BY FRED B SEELY
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Part II

THE FLOW OF WATER THROUGH SUBMERGED ORIFICES

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PART II

THE FLOW OF WATER THROUGH SUBMERGED ORIFICES

IV. INTRODUCTION

9. *Preliminary.*—Part II of this bulletin presents the results of experiments on submerged sharp-edged orifices of various shapes and sizes discharging under moderately low and under very low heads. The orifices used were of three shapes, circular orifices with diameters from 1 in. to 6 in., square orifices with sides from ½ in. to 5½ in., and rectangular orifices having one side range from ½ in. to 2 in., the other side being 6 in. in each case. The coefficient of discharge is given for each orifice for a velocity range of approximately ½ ft. per sec. to 4 ft. per sec. This range corresponds roughly to a range of head on the orifice of 0.006 ft. to 0.08 ft.

Considerable experimenting has been done on orifices discharging into air, particularly on sharp-edged circular orifices of rather small size although the results are somewhat discordant. Comparatively little experimental work, however, has been carried out on submerged orifices. While the orifice has lost some of its importance as a water measuring device due to the development of other methods, it is, nevertheless, of importance to determine how the rate of discharge is affected by the shape and the size of the orifice and also by the head on the orifice, particularly the effect of very low heads which the submerged orifice makes possible.

The submerged orifice may be of particular importance in cases which require the measurement of water with as small a loss of head as possible as, for example, in determining the discharge from a water turbine when operating under a low head. The decrease in the available head on the turbine made necessary by the proper setting of a weir may be an important factor in the installation.

There is a feeling among some engineers that the importance of the so-called standard orifice (sharp edges, complete contraction without velocity of approach, etc.) has been over-emphasized and that beveled-edged orifices are better adapted at least to conditions where the orifice may be obstructed and the edge soon worn off, as, for example, in measuring the water supplied to water wheels through flume or bulkhead openings. There exist, no doubt, some grounds for this feeling. A sharp edged orifice (an opening in a thin plate), however, is subject to less variation in its construction than a beveled-edged orifice. This fact is of considerable importance where accuracy is essential. It is felt that the submerged orifice, both beveled-edged and sharp-edged, is worthy of more attention than has been accorded it.

10. *Acknowledgment.*—The experimenting was done in the Hydraulic Laboratory of the University of Illinois. Some of the results herein presented have been taken from the theses of W. R. Robinson of the class of 1906 and G. D. Phillips of the class of 1907, and some of the results also, particularly at the low heads, have been taken from a second thesis presented by Mr. Robinson in 1909. All the thesis work was conducted under the direction of Professor Arthur N. Talbot. The careful way in which this preliminary experimenting was done has made the results of the theses of much value. During 1914 and 1915 the writer spent considerable time in checking the results of the theses work and extending certain parts of the investigation.

V. Apparatus and Method of Experimenting

11. *Orifices.*—The orifices used were of three different shapes. Four of the orifices were circular with diameters of 1 in., 2 in., 4 in., and 6 in. Five were square with sides of ½ in., 1 in., 2 in., 4 in., and 5½ in. Three were rectangular with dimensions of ½ in. by 6 in., 1 in. by 6 in., and 2 in. by 6 in. In each case the orifice was formed in a cast iron plate ½ in. thick and 10½ in. in diameter, a sharp edge being formed by beveling at 45 degrees. Except for a few small nicks the edges were sharp and the areas closely true to shape. The dimensions of the orifices were carefully determined (except for the 1-in. circular orifice) by an inside micrometer for dimensions greater than 1 in. and inside screw calipers for dimensions less than 1 in. A list of the orifices used and the areas as determined from the measured dimensions are given in Table 4. The 1-in. circular orifice was broken before

Table 4

List of Orifices Used

Form of Orifice	Nominal Size	Measured Area square feet
Circular	1 in. diam.	not measured
	2 in. diam.	0.0219
	4 in. diam.	0.0883
	6 in. diam.	0.1967
Square	½ in. by ½ in.	0.001735
	1 in. by 1 in.	0.00698
	2 in. by 2 in.	0.0279
	4 in. by 4 in.	0.1109
	5½ in. by 5½ in.	0.2105
Rectangular	½ in. by 6 in.	0.0206
	1 in. by 6 in.	0.0418
	2 in. by 6 in.	0.0838

its dimensions were taken so that the nominal diameter (1 in.) has been used in the calculations. There may be some error, therefore, in the results for this orifice.

12. *Tank Used and Method of Experimenting.*—The same tank was used in all the experiments, the dimensions and general arrangement of which is shown in Fig. 11.* The tank was divided into two compartments by a vertical partition in which the orifice was placed, holding the orifice in a vertical plane.

The water coming from the laboratory standpipe was supplied to the tank through a 6-in. supply pipe and also through a $\frac{3}{4}$-in. pipe, the latter making possible a finer adjustment in maintaining a constant head. After passing through baffle boards the water flowed through the orifice and finally left the downstream compartment by passing out through small openings in the end of the tank, the flow through which was regulated by placing stoppers in some of the holes. These holes were arranged in two narrow portions in the end of the tank, one near each side of the tank, and the stoppers were arranged so as to give nearly a uniform distribution from each of the two sets of openings. This arrangement, it was found, helped to maintain steady conditions.

The quantity of water discharged was determined by weighing for the small discharges and by measuring in a pit for the larger discharges. The pit was about 6 ft. deep, and 7.995 ft. in diameter. The value for the diameter is the average of a large number of readings of a micrometer attached to a rigid stick. The rise in the pit was determined by a vertical graduated rod which could be read directly to 0.02 ft. and to 0.004 ft. by estimating. A float was attached to the bottom of the rod and a still basin was provided. The water was wasted into another pit through a movable spout until the surface of the water in the measuring pit became fairly still so that an accurate reading of the rod could be taken. A hook gage was used to test the accuracy of the float and rod. At the end of the experiment the water was again wasted in the same manner. A calibrated stop watch gave the time corresponding to the rise in the pit.

The head causing flow through the orifice is the difference in the levels of the water surfaces in the two compartments of the tank. This head was measured in nearly all the experiments by means of hook gages. These gages were read directly to 0.001 ft. and to 0.0005 ft. by estimating. Vertical 2-in. pipes attached toward the bottom of the tank served as still basins for the hook gages. The level of the water in the upstream compartment was determined by the use of one

*A view of the tank is shown in Fig. 5 of Bulletin No. 96 of the Engineering Experiment Station of the University of Illinois.

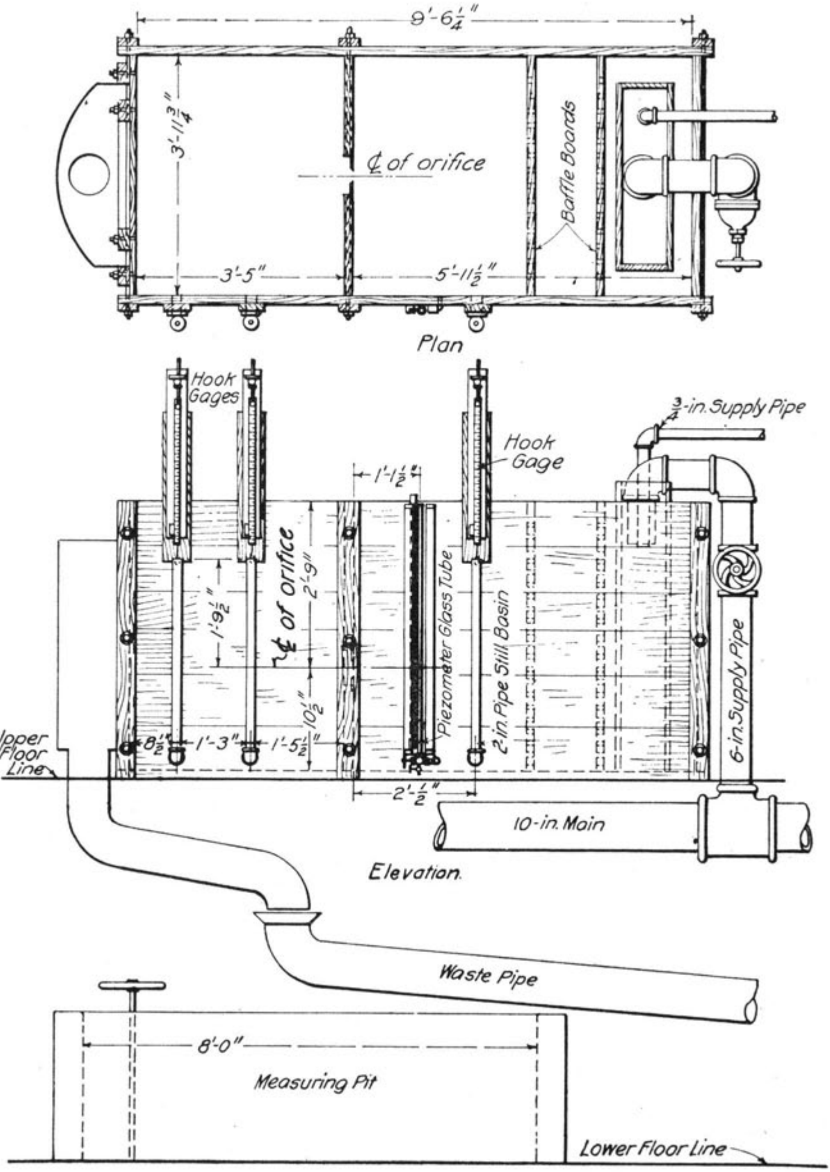

Fig. 11. Tank Used and Arrangement of Apparatus

hook gage only, while two gages were used on the downstream compartment in the earlier experiments. It was found, however, that for the lower heads the two gages gave practically the same result, while for the higher heads the gage nearer the partition gave less fluctuation. For these reasons and because of less difficulty in getting simultaneous readings of only two gages, it was decided to take readings with one gage only on each compartment.

Zero readings of the hook gages were obtained by reading the gages when the tank was nearly full and when no water was allowed to escape, the levels of the water surfaces in the two compartments then being the same. Zero readings were taken frequently during the experimenting.

For most of the heads above 0.3 ft., the head was measured by two vertical peizometer glasses, one attached near the bottom of each compartment, the difference in readings of which (corrected for zero reading) gave the head to 0.001 ft. These two methods overlapped somewhat so that certain heads were measured by both methods.

Leakage from the tank and from the measuring pit was determined several times during the progress of the experimenting and was found to be negligible.

An experiment or run consisted of the following: A sufficient number of stoppers was removed from the end of the tank to give the desired discharge and the inflow through the 6-in. and ¾-in. pipes was then adjusted until the difference in levels of the water surfaces in the two compartments of the tank became constant. The ¾-in. supply pipe was used to make the final adjustment of the head and to hold the head constant throughout the experiment. After obtaining a constant head, the waste pipe shown in Fig. 11 was pulled from beneath the discharge pipe, thus allowing the water to discharge into the measuring pit until the rise in the pit was sufficient to allow its measurement without appreciable error and also to allow time for an accurate measurement of the head. The head was taken as an average of from two to ten readings of the hook gages, the larger number being necessary with the higher velocities on account of the greater fluctuations of the water levels due to the more turbulent conditions of the water, especially in the downstream compartment. Each experiment was repeated, as a rule, three times, although in some cases as many as eight or ten runs were made.

13. *Method of Calculating the Coefficient of Discharge.*—The head, h, causing flow through the orifice is the difference in the levels of the water surfaces in the two compartments of the tank. The ideal rate of discharge is $A\sqrt{2gh}$ in which A is the area of the orifice in square feet and g is the acceleration due to gravity in feet per second per second; hence the coefficient of discharge, c, is found from,

$$c=\frac{q}{A\sqrt{2gh}}$$

where q is the measured rate of discharge in cubic feet per second, as determined from the measured weight or volume discharged and the corresponding time.

VI. Experimental Results and Discussion

14. *Coefficients of Discharge.*—Fig. 12, 13, and 14 show the experimental values of the coefficients of discharge for the various orifices tested. Each plotted point represents the average of from two to ten experiments at practically the same head. It will be noted that

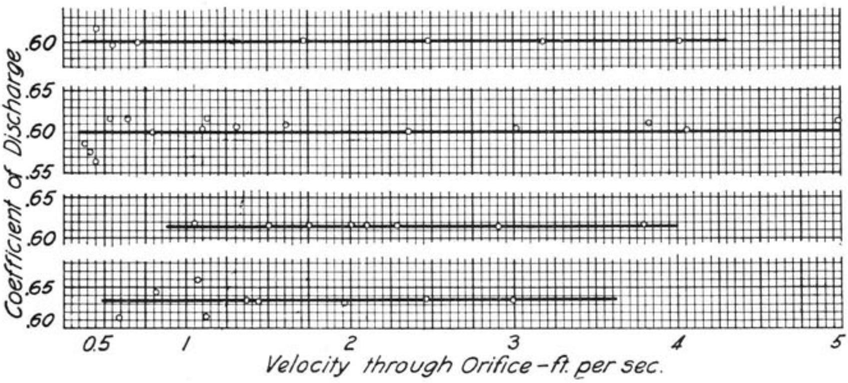

Fig. 12. Diagrams Showing Values of Coefficients of Discharge of Circular Submerged Orifices for Various Velocities

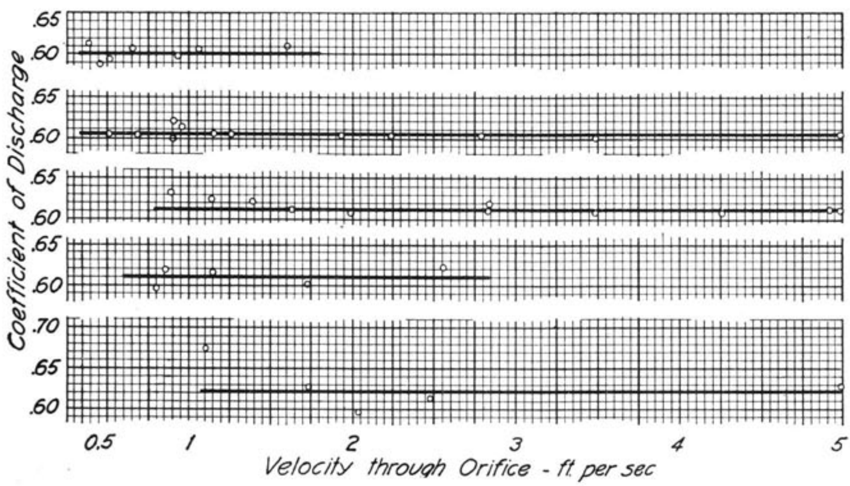

Fig. 13. Diagrams Showing Values of Coefficients of Discharge of Square Submerged Orifices for Various Velocities

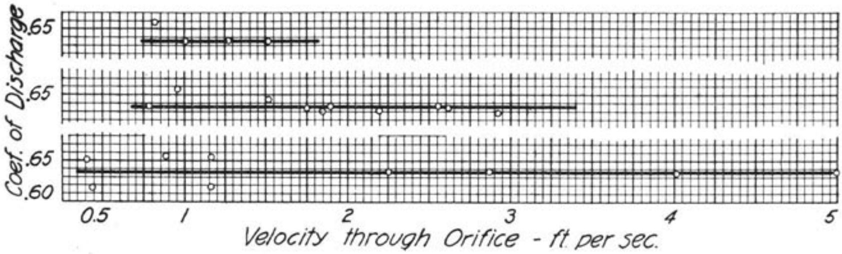

FIG. 14. DIAGRAMS SHOWING VALUES OF COEFFICIENTS OF DISCHARGE OF RECTANGULAR SUBMERGED ORIFICES FOR VARIOUS VELOCITIES

for any given orifice the coefficient is constant for the whole range of velocity used in these experiments which in most of the cases is about ½ ft. per sec. to 4 or 5 ft. per sec. This velocity range corresponds roughly to a range in head of 0.006 to 0.08 ft. and as may be expected the values of the coefficient show the greatest variation at the very low heads.

TABLE 5

VALUES OF COEFFICIENT OF DISCHARGE FOR SUBMERGED ORIFICES FOR VELOCITIES FROM ONE-HALF TO FIVE FEET PER SECOND

Kind of Orifice	Nominal Size	Coefficient of Discharge
Circular	1 in. diameter	0.635[1]
	2 in. diameter	0.615
	4 in. diameter	0.600
	6 in. diameter	0.600
Square	½ in. by ½ in.	0.620
	1 in. by 1 in.	0.610
	2 in. by 2 in.	0.610
	4 in. by 4 in.	0.605
	5½ in. by 5½ in.	0.600
Rectangular	½ in. by 6 in.	0.635
	1 in. by 6 in.	0.635
	2 in. by 6 in.	0.635

[1] Probably somewhat in error since diameter was not measured; nominal diameter used in calculations.

Table 5 and Fig. 15, 16, and 17 show how the coefficient of discharge for the orifices of any given shape varies with the diameter or

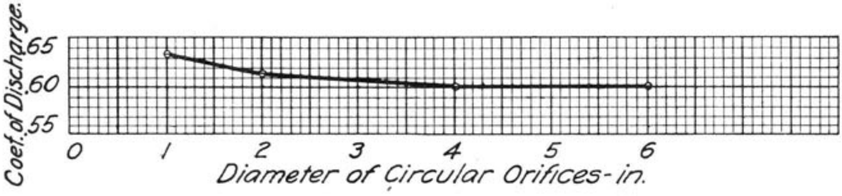

FIG. 15. CURVE SHOWING THE RELATION BETWEEN COEFFICIENT OF DISCHARGE FOR CIRCULAR ORIFICE AND DIAMETER OF ORIFICE

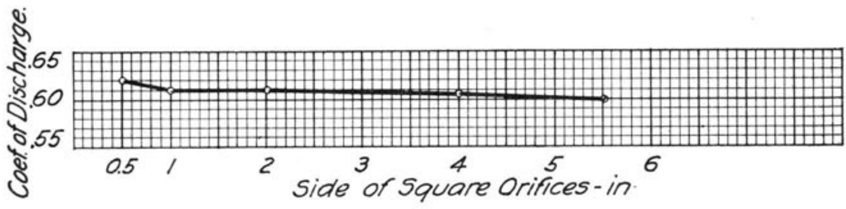

FIG. 16. CURVE SHOWING THE RELATION BETWEEN COEFFICIENT OF DISCHARGE FOR SQUARE ORIFICE AND SIDE OF ORIFICE

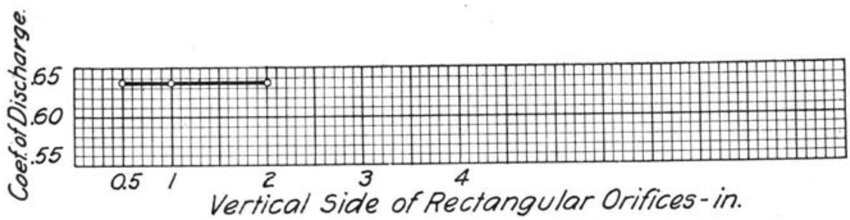

FIG. 17. CURVE SHOWING THE RELATION BETWEEN COEFFICIENT OF DISCHARGE OF RECTANGULAR ORIFICE AND SHORT SIDE OF ORIFICE (OTHER SIDE BEING SIX INCHES IN EACH CASE)

side of the orifice, while from Fig. 18 a comparison may be made between the coefficients of discharge for the different shaped orifices on the basis of their areas. These figures show that the coefficient of discharge for circular and square orifices decrease as the size increases until an area of 8 or 10 square inches is reached after which the coefficient has a constant value of not far from 0.60. This indicates that complete contraction does not take place with the smaller orifices. Because of the uncertainty of the exact diameter there is some doubt, however, concerning the correct value for the 1-in. circular orifice. It will be noted also that the coefficient of discharge for the rectangular orifices

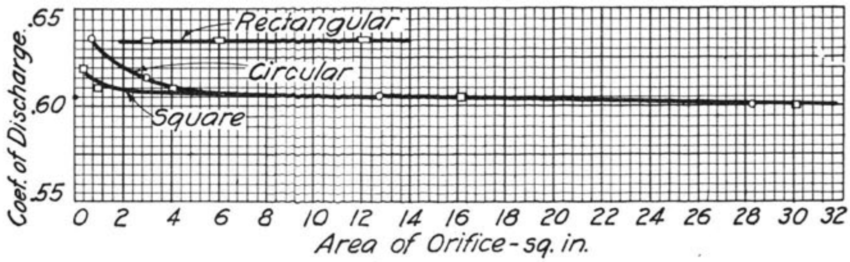

FIG. 18. CURVES SHOWING RELATION BETWEEN COEFFICIENT OF DISCHARGE AND AREA OF ORIFICES

remain constant for the range of areas used in these experiments and that its value is larger than that for circular and square orifices of the same area. Fig. 18 indicates furthermore that as the area of the orifices decreases below 8 sq. in., the coefficient of discharge for circular orifices increases faster than that for square orifices. These observations suggest that the longer side of the rectangular orifices has a controlling influence in determining the rate of discharge for a given head and that the corners of a small square orifice are inefficient in discharging water as compared with the form of a circular orifice of the same area.

15. *Results Obtained by Earlier Experimenters.*—In order to compare the results given in this bulletin with those of earlier investigations and to extend the study to include higher heads and velocities, the results given in Table 6 have been condensed from available published data. It will be noted that the results are not entirely concordant, but considering the different arrangements and methods of measuring the head and the rate of discharge, the results show a very good agreement. The low value of the coefficient of discharge found by Francis is due no doubt to the fact that the rate of discharge was measured over a weir on which the head was rather small. From Table 6 it will be seen that in some of the earlier investigations the coefficient of discharge increased slightly with the head while in others the coefficient decreased, and in still others it showed no systematic change. In all cases the value of the coefficient of discharge is not far from 0.60. The small square orifice (1.2 in. by 1.2 in.) used by Hamilton Smith gave a slightly larger coefficient than the circular orifice with a diameter of 1.2 inches. This result is the reverse of that found in the experiments described in this bulletin. The values also of the coefficient of discharge for circular and square oriffices as found by

Table 6

Results Obtained by Earlier Experimenters on Submerged Sharp-edged Orifices

Circular Orifices

Source	Diameter inches d	Head feet h	Coefficient of Discharge c
Francis	1.22	1.024 1.324 1.490 1.499 1.514	.592 .592 .592 .593 .591
Hamilton Smith, Jr.	0.6	0.437 2.16 4.08	.6183 .6041 .6016
Hamilton Smith, Jr.	1.2	0.250 0.648 0.985 1.51 2.00 2.58 2.99 3.57 3.97	.6048 .6027 .6025 .6006 .6006 .5997 .5989 .5987 .5992
Ellis	12.0	2.60 4.71 6.41 8.10 8.80 12.09 14.25 16.29 18.66	.607 .590 .606 .599 .600 .600 .601 .602 .599
Balch	12.0	0.145 0.469 0.851 1.254 1.612 2.012 2.421 2.949 3.410 4.015	.5909 .5902 .5912 .5993 .5921 .5924 .5954 .5967 .6006 .6054

Square Orifices

Source	Dimensions inches	Head feet h	Coefficient of Discharge c
Hamilton Smith, Jr.	0.6 by 0.6	0.35 2.21 4.06	.6201 .6092 .6068
Hamilton Smith, Jr.	1.2 by 1.2	0.207 0.410 0.771 1.52 2.32 3.11 3.95	.6117 .6091 .6053 .6055 .6040 .6052 .6048
Ellis	12 by 12	2.32 3.92 7.99 11.58 14.31 16.22 18.45	.600 .602 .606 .605 .611 .606 .606
Balch	12 by 12	0.363 0.750 0.771 0.826 0.905 1.134 1.371 2.097 2.636 3.220 3.975	.5940 .5940 .5932 .5982 .5950 .5960 .5970 .6056 .6105 .6095 .6148
Stewart	48 by 48 (3.72 in. thick)	.05 .10 .15 .20 .25 .30	.626 .608 .605 .605 .606 .610

Rectangular Orifices

Source	Dimensions inches	Head feet h	Coefficient of Discharge c
Hamilton Smith, Jr.	0.6 by 3.6	0.614 1.63 2.77	.6219 .6207 .6188

Hamilton Smith are slightly less than those herein reported in Table 5. Omitting the values as given by Francis it will be observed that there is very little difference between the coefficients for the small and the large orifices, the value of the coefficient varying only slightly from 0.60. From the results obtained in the present investigation as given in Table 5 and in Fig. 12, 13, and 14, it will be seen that the coefficient varies more with the size of the orifice than is shown by the results of the earlier experiments, as given in Table 6.

It will be observed also that the coefficient of discharge for the rectangular orifice used by Hamilton Smith is somewhat smaller than that herein reported. It may seem that the diverging sides of the orifices used in the experiments reported in this bulletin (orifice plate ½-in. thick) would form a diverging mouthpiece, particularly in the case of the smaller orifices, but experiments* on diverging mouthpieces have shown that a mouthpiece having a total angle of divergence of 90 degrees has very little, if any, effect on the rate of discharge.

16. *Comparison with Discharge into Air.*—The experiments on sharp-edged orifices with discharge into air are more numerous than for submerged discharge. The experiments of Bilton and to a less degree those by Judd and King, and those by Mair and by Ellis indicate that there is a critical head for each circular orifice above which the coefficient remains constant. Bilton concludes that "circular orifices of 2½-in. diameter, and over, under heads of 17 in., and over, have a common coefficient of discharge lying between 0.59 and 0.60 but which is probably about 0.598 (subject to the head being not less than 2 or 3 diameters)." The results of the experiments of Hamilton Smith, as is well known, indicate that the coefficient of discharge gradually decreases as the size of the orifice increases, and also decreases as the head increases until at a head of 100 ft. all orifices, regardless of the size or the shape, have a common coefficient of discharge.

The results of the experiments on submerged orifices herein reported seem to indicate, as previously noted, that orifices having diameters greater than about 2½ in. (or sides, if square) have a common coefficient of discharge which is very close to 0.60. There seems, however, to be no evidence of a critical head since the coefficient remains constant for the whole range of head used, nor is there evidence of a critical head in the results obtained by earlier experimenters on submerged orifices as given in Table 6.

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*"The Effect of Mouthpieces on the Flow of Water Through a Submerged Short Pipe." Univ. of Ill. Eng. Exp. Sta., Bul. 96, 1917.

From a study of the experimental results on orifices with discharge into air it is believed that the coefficient of discharge for submerged orifices are the same as those for discharge into air for the same heads and sizes and shapes (except for very small heads). It is doubtful if the statement sometimes made, namely, that the coefficient of discharge for submerged orifices is about one per cent less than that for free discharge, is justified.

17. *Summary.*—The following brief summary is given as applying to submerged sharp-edged orifices for velocities from ½ to 5 ft. per sec.

(1) The coefficient of discharge for a circular, a square, or a rectangular submerged orifice does not vary with the velocity.

(2) Circular and square submerged orifices having areas greater than about 10 sq. in. have a common coefficient of discharge varying but little from 0.60.

(3) Rectangular submerged orifices having one side from 3 to 12 times the other side have a constant coefficient of discharge which is larger than that for circular and square orifices of the same size, particularly for the larger areas, at least up to a size of 12 sq. in.

(4) The flow of water through submerged sharp-edged orifices is very nearly the same as that for the same kind of orifices with discharge into air, provided the head is not less than 2 or 3 diameters when the discharge is into air.

PART III

FIRE STREAMS FROM SMALL HOSE AND NOZZLES

By VIRGIL R FLEMING
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Part III

FIRE STREAMS FROM SMALL HOSE AND NOZZLES*

VII. Introduction

18. *Scope of Experiments.*—Part III presents the results of experiments on 1½-in. hose and nozzles. Both rubber-lined hose and unlined linen hose were used. Three sizes of conical nozzles were tested, the diameters of the nozzle openings being 5/16 in., 7/16 in., and ½ in.

The loss of head in the hose due to friction and the corresponding friction factor are given for each hose for a range in velocity from about 4 to 8 ft. per sec. The coefficient of discharge for each nozzle is recorded for a range in pressure at the base of the nozzle from about 10 to 85 lb. per sq. in. The height and the horizontal distance which the jets reached are also recorded. The influence of a cylindrical tip on a nozzle is brought out and some discussion is given concerning the quantity of water required for temporary fire protection for the interior of buildings.

The importance of adequate fire protection has become so well recognized that most buildings, even those of moderate size, are equipped with some sort of fire apparatus for immediate service in case of fire in the interior of the building and until the city fire department arrives. The ordinary water buckets and portable chemical fire extinguishers have in a large measure been supplemented with small fire hose. Few data are available concerning the hydraulics of small fire streams. Many inquiries concerning the discharge from small nozzles and the loss of head in small hose led to the tests which are herein described. The tests were undertaken with the object of acquiring data and putting the results into so workable a form that it would be easy to compute the quantity of water delivered by a nozzle of the size ordinarily used in the fire protection of the interior of buildings or to compute the pressure necessary in the mains to give an effective fire stream from such nozzles, and also to throw some light upon the quantity of water which would be considered sufficient for temporary protection.

* The experiments used in Part III of this Bulletin were reported in the Proceedings of the Fifth Meeting of the Illinois Water Supply Association, p. 170, 1913.

19. *Acknowledgment.*—The experiments here used were conducted at the University of Illinois under the direction of the writer by E. O. Korsmo and A. B. Neininger of the class of 1911 as thesis work. Much credit is due them for the care and thought given the problem and the thoroughness with which they did their work. The water for the experiments was drawn from the University mains. The experiments for determining the height and the horizontal distance the jets would reach were conducted out of doors. The other experiments were carried on in the Hydraulics Laboratory.

VIII. Apparatus and Method of Experimenting

20. *Hose and Nozzles.*—Rubber-lined cotton hose and unlined linen hose having a nominal diameter of 1½ in. were used, the length of the test section for determining the lost head being 50 ft. in each case. The hose taken was from the racks in the University buildings and is representative of hose of this size commonly in use.

Three 1½-in. conical nozzles having different sizes of openings, as shown in Fig. 19, were tested. The first nozzle had a diameter of

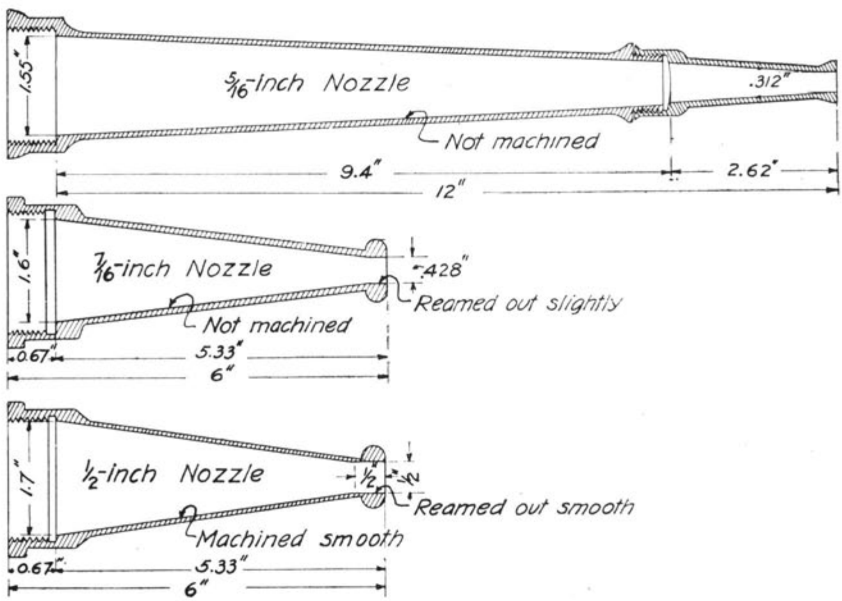

Fig. 19. Longitudinal Sections of Nozzles Tested

5/16 in. The second nozzle had a diameter of 0.428 in., which is approximately 7/16 in., and in compiling the tables, corrections were made so as to apply to a 7/16-in. nozzle. The third nozzle had a diameter of ½ in. The 5/16-in. nozzle was 12 in. long while the other two were only 6 in. long (see Fig. 19). The 5/16-in. and the 7/16-in. nozzles were rough on the interior surfaces, having been left just as they came from the molds, the prints of the sand core being plainly visible. The tips had been smoothed slightly by running a drill through the opening, but the cylindrical portion made by the drill was very short in both cases. The ½-in. nozzle was made from a 7/16-in. nozzle. The entire inner surface was machined smooth and a ½-in. reamer was run through the opening making a cylindrical portion ½ in. long.

21. *Method of Experimenting.*—The loss of head was measured over a length of fifty feet of the hose by means of a differential mercury gage. The average pressure at a section of the hose was obtained with a piezometer connection or coupling of the Freeman type. A cross-section of one of these couplings is shown in Fig. 20. The discharge

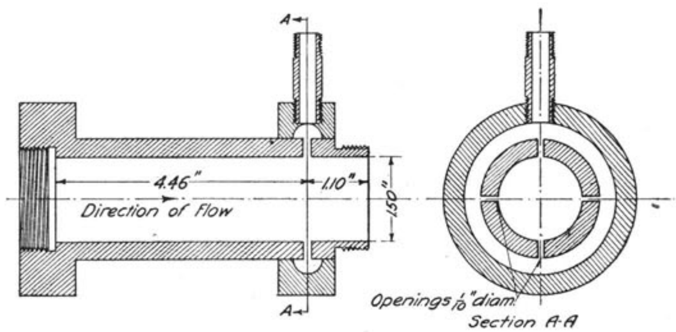

FIG. 20. CROSS-SECTION OF PIEZOMETER COUPLING

through the hose when determining the lost head in the hose was measured with a calibrated nozzle. When determining the coefficient of discharge for the nozzles the discharge was measured by weighing. The pressure at the base of the nozzle was measured with a calibrated pressure gage.

The vertical heights attained by the streams were determined by means of a transit and the horizontal distances reached were found by measuring with a tape from stakes which were driven in the ground at frequent intervals and at known distances from the nozzle.

IX. Experimental Results and Discussion

22. *Results from Freeman's Experiments.*—In 1888 John R. Freeman conducted an extensive series of tests upon 2½-in. fire hose and nozzles.* In general, Freeman arrived at the following conclusions: Smooth conical nozzles give coefficients of discharge as high as any other form of nozzle, the jets reach farther and the streams remain solid for greater distances than for any other form of nozzle of the same size of opening and with the same pressure at the base of the nozzle. For smooth conical nozzles 1⅛ or 1¼ in. in diameter, a coefficient of discharge of 0.977 may be taken with great confidence that it will not be more than one-half of 1 per cent in error. The coefficient will be slightly larger for smaller nozzles. The nozzle makes a very convenient method of measuring water. The friction is but slightly more in smooth rubber-lined hose than in clean iron pipe of the same diameter. The friction in unlined linen hose is about two and one-third times as much as in smooth rubber-lined hose. A hose elongates from 2 per cent to 5 per cent with a pressure of 50 lb. per sq. in. This elongation produces a sinuosity which increases the loss of head about 6 per cent. Care should be exercised that there is no abrupt change of section in the hose couplings and that no washers or gaskets are so left as to impede the flow of water.

It is frequently recommended that a 250 gal. per min. fire stream be used in business districts, while a 175 or a 200 gal. per min. stream may be used in a residential district. These discharges correspond to a nozzle pressure of 40 to 50 lb. per sq. in., and a hydrant pressure of 80 to 110 lb. per sq. in. These values refer to outside service. Table 7 gives data for 2½-in. hose and nozzles for three different sizes of nozzle openings taken from Freeman's results. This table is convenient for making calculations for outside fire protection.

23. *Experimental Data.*—Table 8 gives the more important data of the experiments with hose and nozzles herein reported. Values are given for the pressures at the base of the nozzles, the discharges, the loss of head in the hose, and the vertical and horizontal distances reached by the jets. Other results discussed have been calculated from the data in this table.

* "Experiments Relating to the Hydraulics of Fire Streams." Trans. Am. Soc. Civ. Eng., Vol. XXI, p. 304, 1889.

TABLE 7

FREEMAN'S RESULTS FOR 1-IN. 1⅛-IN. AND 1¼-IN. NOZZLES ATTACHED TO 2½-IN. HOSE

1-INCH NOZZLE

Pressure Base of Nozzle	Discharge	Loss of Head in 100 Feet of Hose		Vertical Height of Jet for Good Fire Stream	Horizontal Distance	
		Rubber Lined	Unlined Linen		Jet for Good Fire Stream	Extreme Drops at Level of Nozzle
Lb. per sq. in.	Gallons per minute	Lb. per sq. in.	Lb. per sq. in.	Feet	Feet	Feet
20	132	5	10	35	37	77
30	161	7	15	51	47	109
40	186	10	20	64	55	133
50	208	12	25	73	61	152
60	228	15	30	79	67	167
70	246	17	35	85	72	179

1⅛-INCH NOZZLE

Pressure Base of Nozzle	Discharge	Loss of Head in 100 Feet of Hose		Vertical Height of Jet for Good Fire Stream	Horizontal Distance	
		Rubber Lined	Unlined Linen		Jet for Good Fire Stream	Extreme Drops at Level of Nozzle
Lb. per sq. in.	Gallons per minute	Lb. per sq. in.	Lb. per sq. in.	Feet	Feet	Feet
20	168	8	16	36	38	80
30	206	12	25	52	50	115
40	238	16	33	65	59	142
50	266	20	41	75	66	162
60	291	24	49	83	72	178
70	314	28	57	88	77	191

1¼-INCH NOZZLE

Pressure Base of Nozzle	Discharge	Loss of Head in 100 Feet of Hose		Vertical Height of Jet for Good Fire Stream	Horizontal Distance	
		Rubber Lined	Unlined Linen		Jet for Good Fire Stream	Extreme Drops at Level of Nozzle
Lb. per sq. in.	Gallons per minute	Lb. per sq. in.	Lb. per sq. in.	Feet	Feet	Feet
20	209	12	25	37	40	83
30	256	19	38	53	54	119
40	296	25	51	67	63	148
50	331	31	63	77	70	169
60	363	37	76	85	76	186
70	392	43	88	91	81	200

TABLE 8

RESULTS OF EXPERIMENTS AT UNIVERSITY OF ILLINOIS WITH 5/16-IN., 7/16-IN. AND ½-IN. NOZZLES ATTACHED TO 1½-IN. HOSE

5/16-INCH NOZZLE

Pressure Base of Nozzle	Discharge	Loss of Head in 100 Feet of Hose		Vertical Height of Jet for Good Fire Stream	Horizontal Distance	
		Rubber Lined	Unlined Linen		Jet for Good Fire Stream	Extreme Drops at Level of Nozzle
Lb. per sq. in.	Gallons per minute	Lb. per sq. in.	Lb. per sq. in.	Feet	Feet	Feet
20	12	.7	1.3	28	15	53
30	15	1.1	1.9	32	18	63
40	17	1.5	2.6	34	21	71
50	19	1.8	3.2	35	23	78
60	21	2.2	3.9	36	26	84
70	23	2.6	4.5	37	28	90
80	24	2.9	5.2	38	29	96
90	26	3.3	5.9	39	30	102
100	28	3.7	6.5	40	31	107

7/16-INCH NOZZLE

Pressure Base of Nozzle	Discharge	Loss of Head in 100 Feet of Hose		Vertical Height of Jet for Good Fire Stream	Horizontal Distance	
		Rubber Lined	Unlined Linen		Jet for Good Fire Stream	Extreme Drops at Level of Nozzle
Lb. per sq. in.	Gallons per minute	Lb. per sq. in.	Lb. per sq. in.	Feet	Feet	Feet
20	25	2.8	5.1	23	10	45
30	30	4.2	7.7	27	13	54
40	35	5.6	10.2	30	16	63
50	39	7.0	12.8	32	18	70
60	43	8.5	15.3	33	20	77
70	47	9.8	17.8	34	21	84
80	50	11.1	20.3	35	23	94
90	53	12.7	22.9	36	24	99
100	56	14.1	25.5	37	25	106

½-INCH NOZZLE

Pressure Base of Nozzle	Discharge	Loss of Head in 100 Feet of Hose		Vertical Height of Jet for Good Fire Stream	Horizontal Distance	
		Rubber Lined	Unlined Linen		Jet for Good Fire Stream	Extreme Drops at Level of Nozzle
Lb. per sq. in.	Gallons per minute	Lb. per sq. in.	Lb. per sq. in.	Feet	Feet	Feet
20	33	5.2	9.5	34	15	63
30	40	7.7	14.4	37	20	79
40	46	10.2	18.8	38	25	91
50	52	12.8	23.8	39	30	102
60	57	15.4	28.5	40	33	111
70	61	18.0	32.7	41	37	120
80	65	20.5	38.4	42	40	127
90	69	23.0	42.0	43	43	134
100	73	25.6	47.0	44	46	140

24. *Friction Factors.*—The curves of Fig. 21 show the friction factors for each kind of hose used and for velocities in the hose ranging

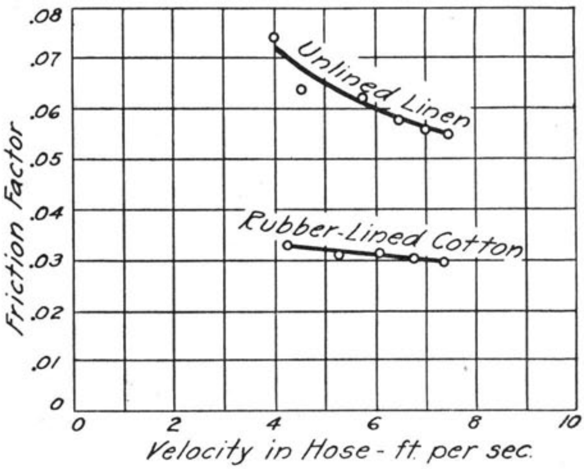

FIG. 21. DIAGRAM SHOWING FRICTION FACTORS IN RUBBER-LINED AND UNLINED HOSE

from 4 to 8 ft. per sec. These curves cover the range of velocities which would be met in ordinary use. The friction factor f is computed from the formula

$$h = \frac{fl}{d} \frac{v^2}{2g}$$

h = head lost in feet of water
l = length of hose in feet
d = diameter of hose in feet
v = velocity of the water in the hose in feet per second
g = acceleration due to gravity in feet per second per second

The loss of head in the rubber-lined hose varies almost directly as the square of the velocity and is about the same as the loss of head in clean iron pipe of the same diameter. The friction factor for the unlined linen hose decreases as the velocity increases, or in other words the loss of head does not vary directly as the square of the velocity, the ratio of the lost head to the square of the velocity being larger for the lower velocities. The reason that the friction factor for unlined linen hose decreased more rapidly with the velocity than does that for rubber-lined cotton hose may be that the diameter of the unlined hose is increased more than that of the rubber-lined cotton hose by the increasing pressures which accompany the increasing velocities. This would make the value of d larger and the value of v smaller in the equation for f than was actually used. It is probable, furthermore, that the increasing pressure decreases the roughness of the unlined linen hose more than it does for rubber-lined hose. In general the lost head in the unlined linen hose is about twice as great as in the rubber-lined cotton hose. If an average value of the friction factor (0.06) is used for the unlined linen hose, no great error will enter into the results under ordinary circumstances. The length of hose will ordinarily not be mose than 100 feet and for this length about 10 lb. per sq. in. will be the maximum loss of head in the unlined linen hose under working conditions with nozzles giving streams up to ½ in. in diameter. An error as large as 10 per cent in the calculation of the loss of head in the hose would affect the nozzle pressure not more than one pound per square inch.

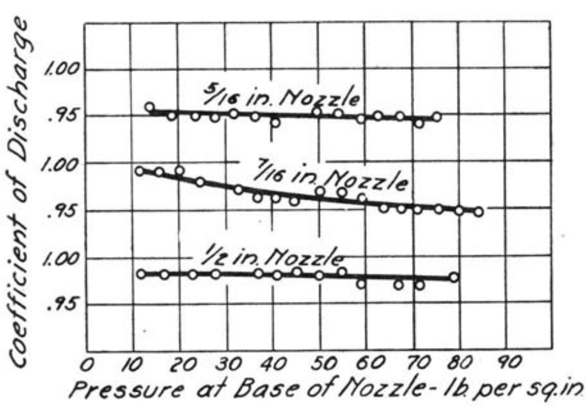

FIG. 22. DIAGRAM SHOWING COEFFICIENTS OF DISCHARGE OF NOZZLES

While the loss of head in the unlined linen hose is about twice as great as the loss of head in the rubber-lined hose, the linen hose has several advantages. It is much lighter to handle, folds up in less space on the wall racks, costs only about 50 to 60 per cent of the cost of rubber-lined hose and, in an ordinary building, its life is much longer.

25. *Coefficients of Discharge.*—The coefficients of discharge for each of the three sizes of nozzles are given in Fig. 22 for pressures

at the base of the nozzle ranging from about 10 to 85 lb. per sq. in. This range of pressures corresponds to a range in the velocity of the issuing jet from a minimum of about 35 ft. per sec. with the ½-in. nozzle to a maximum of about 185 ft. per sec. with the 5/16-in. nozzle. The coefficient of discharge is the ratio of the measured discharge to the ideal discharge. The measured discharge was weighed and the volume computed from the weights. The ideal discharge was computed from the formula

$$q = A\sqrt{2gh}$$

q = discharge in cubic feet per second. A = area of the opening of the nozzle in square feet. g = acceleration due to gravity in feet per second per second. h = pressure at the base of the nozzle in feet of water. The velocity of approach to the nozzle was negligible and was, therefore, not considered in the equation for the ideal discharge. The pressure at the base of the nozzles was measured with calibrated pressure gages.

The coefficient of discharge for the 7/16-in. and the ½-in. nozzles is nearly constant for all pressures and averages 0.98. The coefficient is slightly lower than 0.98 for the 7/16-in. nozzle at the higher pressures. The 5/16-in. nozzle gives a coefficient of 0.95. The 5/16-in. nozzle is 12 inches long while the other two are only 6 inches long, and this greater length adds somewhat to the friction and lowers the coefficient of discharge for the 5/16-in. nozzle.

The 5/16-in. and the 7/16-in. nozzles were rough on the interior surfaces, having been left just as they came from the molds. The tips had been smoothed slightly by running a drill through the opening, but the cylindrical portion made by the drills was very short in each case and the nozzles gave streams which sprayed badly a short distance away. The ½-in. nozzle was made from a 7/16-in. nozzle. The entire inner surface was first machined out in hopes that it would prevent the spraying of the jet, but the nozzle gave a stream which appeared no better than before machining. Then a 15/32-in. reamer and finally a ½-in. reamer were run through the opening, each reducing the spraying. The ½-in. reamer made the cylindrical portion of the opening ½-in. long, and the resulting nozzle gave a very good stream. An opening larger than ½-in. could not be made in the nozzle because of the thinness of the walls.

26. *Height and Horizontal Distance of Jets.*—The heights and the horizontal distances reached by the jets from each of the three nozzles

used are given in Table 8. As stated, the vertical heights were measured by means of a transit and the horizontal distances were measured with a tape from stakes which were driven in the ground at frequent known space intervals. The observations were made when a moderate wind was blowing which interfered with the streams considerably. A stream was considered good for the distance in which practically all the water would pass through a circle whose diameter was 18 inches. The value was an arbitrary selection and the streams might be considered by some as effective for greater distances than those given in Table 8. The streams, however, beyond the sections chosen, diverged rapidly and the selection of a circle larger than 18 inches would have added but a few feet to the distances given in Table 8 in any case.

27. *Effect of Cylindrical Tip.*—The tests show clearly the importance of a smooth cylindrical opening at the tip of the nozzle. A comparison of the results of the tests on the 7/16-in. and the 1/2-in. nozzles for vertical heights and horizontal distances of the jets will show this difference. In the case of the 7/16-in. nozzle with a pressure of 30 lb. per sq. in. at the base of the nozzle the vertical height of the jet was 27 ft. as compared with 37 ft. for the 1/2-in. nozzle for the same pressure. Likewise the horizontal distance reached with the 7/16-in. nozzle was 13 ft. as compared with 20 ft. with the 1/2-in. nozzle. Similar comparisons may be made for other pressures at the base of the nozzle. The appearance of the jets showed a much greater difference than the data would indicate. It must be remembered that the two nozzles were alike and gave streams which appeared to be the same before one was reamed out to a larger size.

It will be noted also that in the case of the 5/16-in. nozzle for a pressure of 30 lb. per sq. in. at the base of the nozzle, the vertical and horizontal distances reached by the stream were respectively 32 and 18 ft., which indicate that the improvement in the carrying capacity of the 1/2-in. nozzle over that of the 7/16-in. nozzle was not due to the smoother condition of the interior surface of the 1/2-in. nozzle, but rather to the effect of the cylindrical tip. The condition of the interior surface of the nozzle to within one-half inch of the end does not seem to affect appreciably either the quantity of discharge or the quality of the stream.

It seems important, therefore, that the tip of the nozzle should be reamed out for a distance of at least 1/2 in. in order to obtain a good fire stream. It is probably true also that for nozzles somewhat larger than those used in these experiments the length of the cylindrical portion should be more than ½ in., perhaps equal to the diameter of the issuing stream.

28. *Requirements for Temporary Fire Protection for the Interior of Buildings.*—Small fire hose and nozzles should be used as a temporary protection and brought into play until greater relief is at hand. They must necessarily operate under ordinary working pressures in the mains more often than under fire pressures. With 40 lb. per sq. in. as an average pressure in the mains, there should be, after deducting for losses in the hose and connecting pipes, about 30 lb. per sq. in. at the nozzle. This pressure, of course, would be still further reduced if the nozzle used was at a higher elevation than the main. With a nozzle pressure of 30 lb. per sq. in. the ½-in. nozzle will discharge 40 gal. per min., the 7/16-in. and the 5/16-in. nozzles will discharge 30 and 15 gal. per min., respectively. It is felt that the discharge from the two smaller nozzles is not great enough for effective work. It is true that the pressure at the nozzle for the smaller sizes with a given pressure in the main will be somewhat greater than for the ½-in. nozzle, because of the decreased velocity in the hose which will give a smaller loss of head, but this difference in pressure will not be enough to increase the discharge materially for an ordinary length of hose. The discharge from the 5/16-in. nozzle is too small to be very effective even at higher pressures. The discharge for a pressure of 100 lb. per sq. in. is but 28 gal. per min. It is recommended that ½-in. nozzles be used with 1½-in. hose. For nozzles larger than ½ in., the discharge would become greater and increase the loss of head in the hose to such an extent that there would not be enough nozzle pressure left to produce a stream which would carry a sufficient distance.

With the aid of the tables the discharge for any of the nozzles may be readily computed for any pressure in the mains. If the nozzle is at a higher elevation than the main, subtract from the pressure in the main an amount equal to 0.434 times the difference in elevation in feet between the nozzle and the main. Take a discharge from the table for any pressure at the base of the nozzle for the size of nozzle used, then take the corresponding value of the head lost in the kind of hose used, multiply this value by the length of hose in feet used and divide by 100. The result gives the total loss in the hose for the assumed discharge. If there is any connecting pipe, the loss in it will be the same as the loss in a corresponding length of rubber-lined hose.

Add the losses in the pipe and hose to the pressure at the base of the nozzle for the assumed discharge to obtain the pressure in the main (corrected for the difference in elevation) necessary to produce this discharge. The discharge will vary as the square root of this pressure. Letting q' = the assumed discharge, P' = the pressure in the main (corrected for the difference in elevation) which will produce this discharge, q = the discharge to be determined, P = the actual pressure in the mains and H = difference in elevation between the nozzle and the main in feet gives the relation

$$q=q'\sqrt{\frac{P-0.434H}{P'}}$$

which gives the required discharge.

To illustrate the use of the formula the following assumptions are made. Pressure in mains, $P=60$ lb. per sq. in., 80 ft. of linen hose, 50 ft. of 1½-in. connecting pipe, elevation of nozzle above main 30 ft. and ½-in. nozzle used.

Assume a discharge of 46 gal. per min. and from the table the following values are obtained:

$$\begin{aligned}
&\text{Nozzle pressure} &&= 40\\
&\text{Loss in hose} = \frac{80\times 18.8}{100} &&= 15.0\\
&\text{Loss in pipe} = \frac{50\times 10.2}{100} &&= 5.1\\
&\qquad\text{Total} \quad = &&P' = \overline{60.1}
\end{aligned}$$

Substituting in the formula

$$q=40.7 \text{ gal. per min.}$$

The following method may be used to determine the discharge for any size of nozzle for any pressure in the mains. Assume any pressure at the base of the nozzle, h', in feet of water. The discharge for this pressure may be determined by the formula

$$q'=cA\sqrt{2gh'}$$

q' = discharge in cu. ft. per sec.

c = coefficient of discharge and may be taken as 0.98

A = area of opening of nozzle in sq. ft.

$2g$ = 64.4 ft. per sec. per sec.

Determine the velocity in the hose for this discharge from the formula

$$v = \frac{q'}{a}$$

v = velocity in hose in ft. per sec.
a = area of hose in sq. ft.

Determine the loss in the hose from the formula

$$h_2 = \frac{fl}{d}\frac{v^2}{2g}$$

h_2 = head lost, in feet
f = friction factor which may be taken as 0.03 for rubber lined hose or 0.06 for unlined linen hose
l = length of hose in feet
d = diameter of hose in feet
v = velocity in hose in ft. per sec.
$2g$ = 64.4 ft. per sec. per sec.

If there is any pipe connecting the hose to the main, the loss for it may be computed by the same formula as for the hose, using 0.03 for the friction factor for 1½-in. pipe. Call this lost head h_3.

The pressure in the main to give the assumed nozzle pressure is

$$H' = h' + h_2 + h_3$$

This pressure will be in feet of water. Then using the relation

$$q = q'\sqrt{\frac{H}{H'}}$$

gives the required discharge. If the main is below the nozzle, subtract the difference in elevation in feet from H in the formula.

It is recognized that this method is not strictly accurate since the head does not vary exactly as the square of the discharge, but the results obtained will be close enough for practical use.

29. *Summary.*—The following brief summary is given as applying to small hose and nozzles with velocities in the hose ranging from about 4 to 8 ft. per sec. and with pressures at the base of the nozzle ranging from about 10 to 85 lb. per sq. in.

(1) The friction factor (f in the equation for the lost head, $h = f\,\frac{l}{d}\frac{v^2}{2g}$) for rubber-lined hose varies but little with the velocity in the hose and is nearly the same as for clean iron pipe of the same diameter.

(2) The friction factor for unlined linen hose decreases as the velocity increases. In general the loss of head in unlined linen hose is about twice as great as in rubber-lined hose of the same diameter and for the same velocity.

(3) The nozzle should have a smooth cylindrical tip at least one-half inch long to keep the jet from spraying. A cylindrical tip is a much more important factor in securing a good fire stream than a smooth surface in the interior of the nozzle.

(4) Nozzle openings commonly in use to supply fire streams in the interior of buildings seem too small for adequate temporary fire protection. It is recommended that a nozzle with a ½-in. opening be used with a 1½-in. hose in order to secure a sufficient quantity of water for an effective fire stream.

(5) The coefficient of discharge of a small conical nozzle varies but little with the velocity and is close to 0.98. The value of 0.95 obtained with the 5⁄16-in. nozzle, which was 12 in. long as compared with 6 in. for the other nozzles tested, indicates, however, that the nozzle should be short to obtain the value of 0.98. A cylindrical tip on the nozzle seems to have little influence on the coefficient of discharge.

Part IV

THE ORIFICE BUCKET FOR MEASURING WATER

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THE ORIFICE BUCKET FOR MEASURING WATER

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PART IV

THE ORIFICE BUCKET FOR MEASURING WATER

X. INTRODUCTION

30. *Purpose.*—The purpose of Part IV is to describe a method of measuring water by means of a simple, portable, and inexpensive device, here called an orifice bucket, and to present experimental data applying thereto for a range of conditions sufficient to indicate that the device is reliable for use in engineering practice. An orifice bucket is a cylindrical vessel into which water to be measured falls vertically and passes out through a number of holes or orifices in the bottom. A vertical glass tube placed just outside the bucket is connected to the sides of the bucket near the bottom, and the height of the water in the tube indicates the head on the orifice.

The orifice bucket was devised for the purpose of measuring the discharge of several artesian wells pumped by means of air lift, the water from each of which discharged into a separate cistern or small reservoir through a vertical pipe. In each case the water left the pipe with considerable blast and momentum. Several possible methods for the measurement of the discharge were considered but were thought to be impracticable for various reasons or inapplicable for the particular case. After some preliminary laboratory experimenting an orifice bucket was devised which served very satisfactorily in determining the discharge from each of the wells. It was at first feared that the water would enter the bucket with such a blast that entrained air would enter the vertical glass tube and cause trouble in determining the height of water in the bucket. There was, however, no trouble from this cause and the fluctuations of the water level in the glass tube offered no serious difficulties.

The orifice bucket has also given satisfaction in tests made to determine yields of well pumps of the reciprocating type. It should give satisfactory results in the field where simplicity of construction and portability are desirable and where extreme accuracy is not of great importance.

31. *Acknowledgment.*—The orifice bucket was developed by the writer through experimental work in the Hydraulic Laboratory of the University of Illinois during 1910 and 1911.* Considerable improvement has been made in the arrangement of certain parts of the bucket by I. W. FISK, P. S. BIEGLER, and P. J. NILSEN, of the department of electrical engineering, in connection with tests on electric motor-driven deep-well pumps. Some of the experimental data herein presented were obtained by them, to whom acknowledgment is made.

* A part of the results here presented was published in the Proceedings of the Third Meeting of the Illinois Water Supply Association, p. 87, 1911.

XI. Apparatus and Method of Calibrating

32. *Orifice Bucket.*—Fig. 23 shows the construction and dimensions of one of the first orifice buckets used in the experiments, and Fig. 24 shows the bucket in use. This bucket weighed 23 lb.

As previously stated an orifice bucket is a cylindrical vessel having holes or orifices in its bottom and into which water to be measured

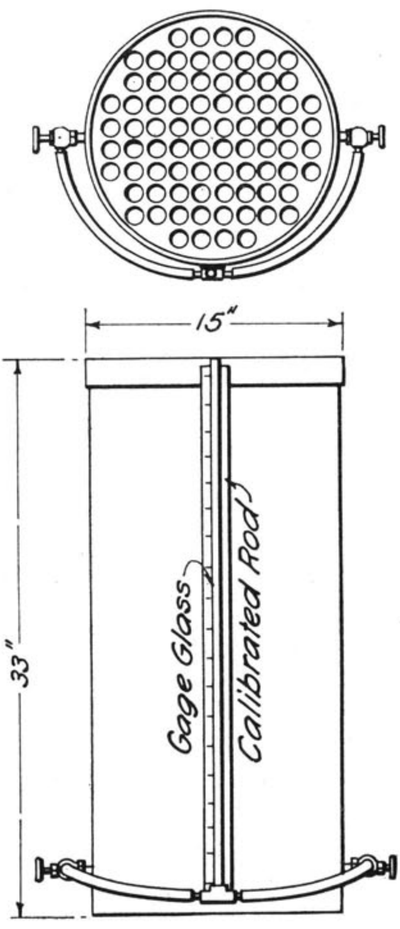

Fig. 23. Fifteen-inch Orifice Bucket Having Fifty-six Orifices

falls vertically, the head of water on the orifices being indicated by the height of the water in a vertical glass piezometer tube attached near the bottom of the bucket.

Fig. 25 shows the construction of the most elaborate orifice bucket which has been used. It is provided with a short tube checker-work to smooth out the flow of the water on its way to the orifices in the

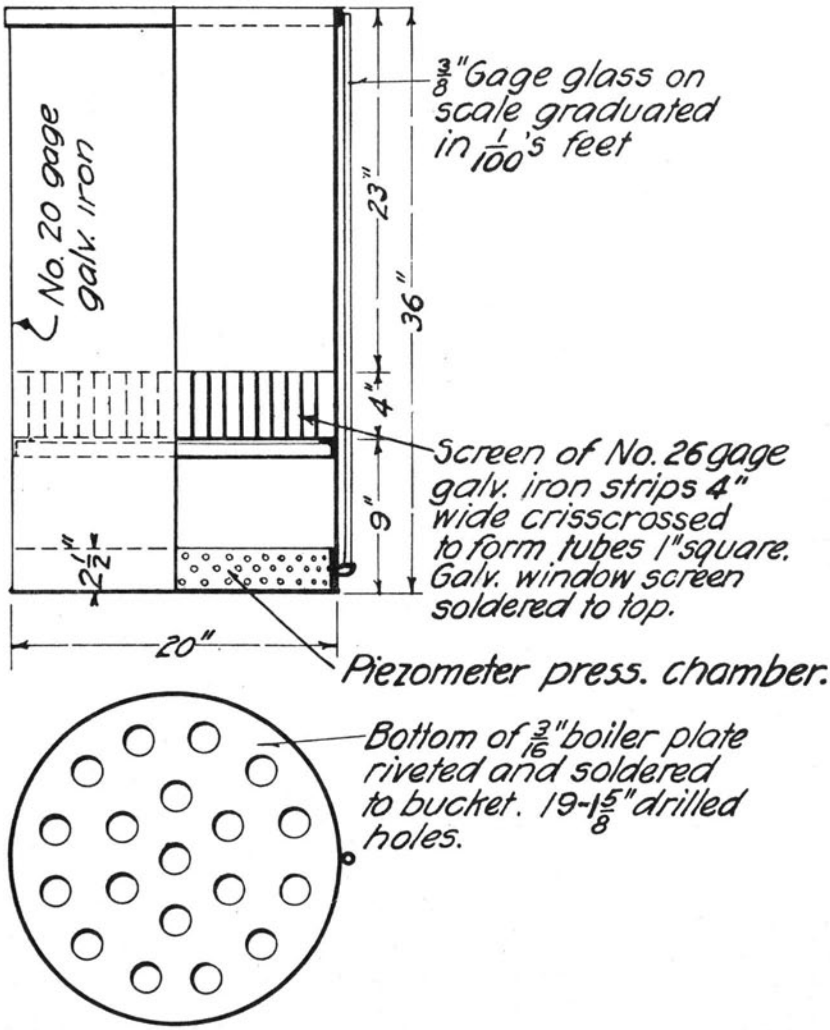

FIG. 25. TWENTY-INCH ORIFICE BUCKET HAVING NINETEEN ORIFICES

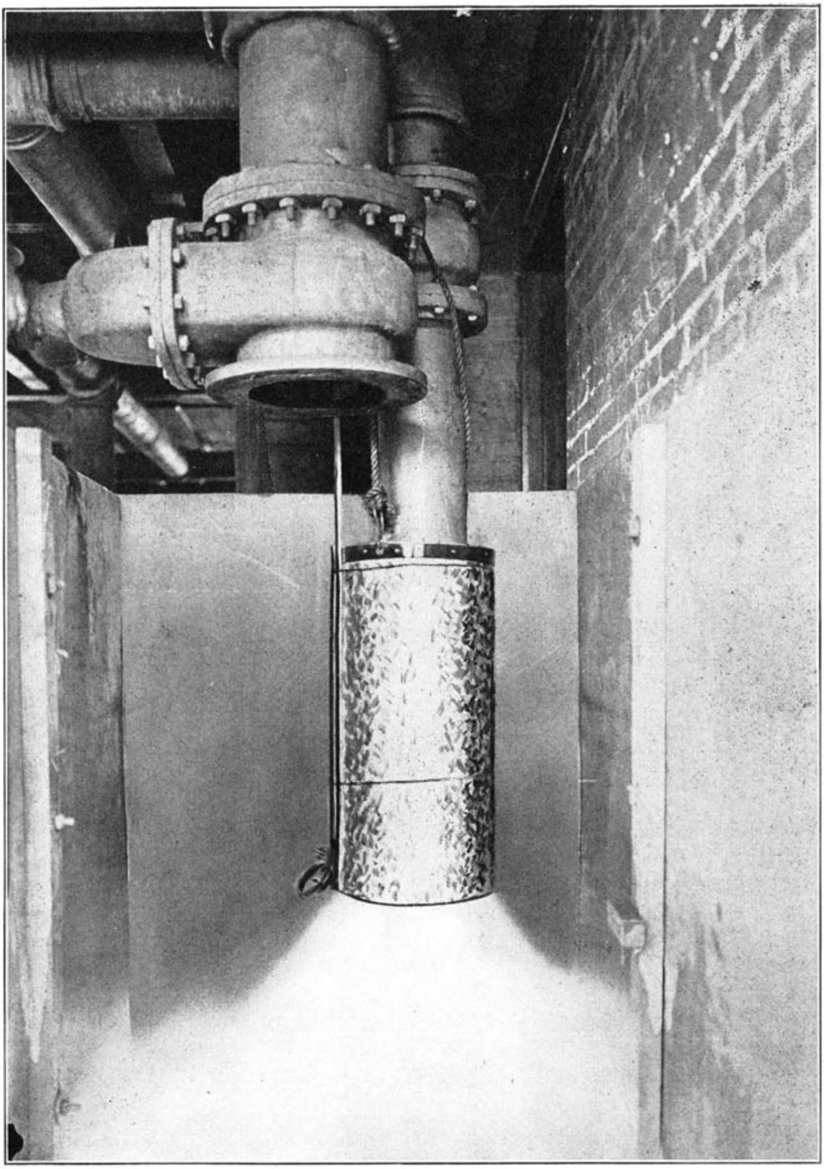

FIG. 24. VIEW SHOWING ORIFICE BUCKET IN USE

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bottom of the bucket. The vertical glass tube is connected to a piezometer chamber or ring around the base of the bucket, pressure being transmitted to the piezometer ring through a large number of small holes.

The orifice bucket may be adapted for the measurement of water for a considerable range in the discharge by varying the head on the orifices and also by varying the number of holes which are stopped or plugged with corks or wooden stoppers. The range in the capacities of the orifice buckets which have been used is from about 40 to 1000 gal. per min.

33. *Method of Calibrating Orifice Bucket.*—In calibrating the orifice bucket it was hung underneath a vertical pipe as shown in Fig. 24. The quantity of water discharged was measured with a 6-in. Venturi meter in most of the calibration tests although a calibrated measuring pit was used in some of the tests to determine the volume discharged in a given time.

With a given number of holes open, the flow in the orifice bucket was regulated by means of a valve between the Venturi meter and the bucket until the height in the bucket remained constant. The Venturi meter reading and the head on the orifices were then taken. This procedure was repeated for several different heads and for different numbers of orifices open.

The effect of varying the conditions of flow was investigated somewhat. The height of the free fall of the water from the inflow pipe to the orifice bucket was varied; likewise different sizes of pipe were used giving different velocities to the stream entering the bucket. The stream was also allowed to enter near to one side of the bucket instead of at the center. Different groupings of the open orifices, furthermore, were tried, and different methods were employed in attempting to spread or distribute the inflowing stream.

In using the orifice bucket it is necessary to estimate the average head shown in the glass tube because there is some fluctuation. The amount of the fluctuation may be reduced by throttling the valve in the connection of the glass tube to the orifice bucket. If the proper conditions are observed, there should be little trouble from this source. It should be remembered that the rate of discharge is proportional to the square root of the head and that the effect of the error which might occur in the head reading itself is thus reduced in determining the discharge.

XII. Experimental Data and Discussion

34. *Fifteen-inch Orifice Bucket Having Fifty-six Orifices.*—Fig. 26 shows the calibration curves for the 15-inch orifice bucket shown in Fig. 23 and 24. There were fifty-six 1-in. holes in the bottom of the bucket giving a maximum capacity of about 1000 gal. per min. With all the orifices open the rate of discharge was varied from about 600 to 1000 gal. per min. by varying the head from about ¾ ft. to 2 ft. With thirty-two orifices open the discharge had a range of about 300 to 600 gal. per min. by varying the head from about ½ ft. to 2.5 ft. In closing the twenty-four orifices, corks were used of such size that they projected but little into the bucket. It was found that in filling the orifices a symmetrical arrangement gave somewhat steadier action, particularly when the orifices near the circumference were the ones filled. The inflowing stream was discharged from an 8-in. pipe. A

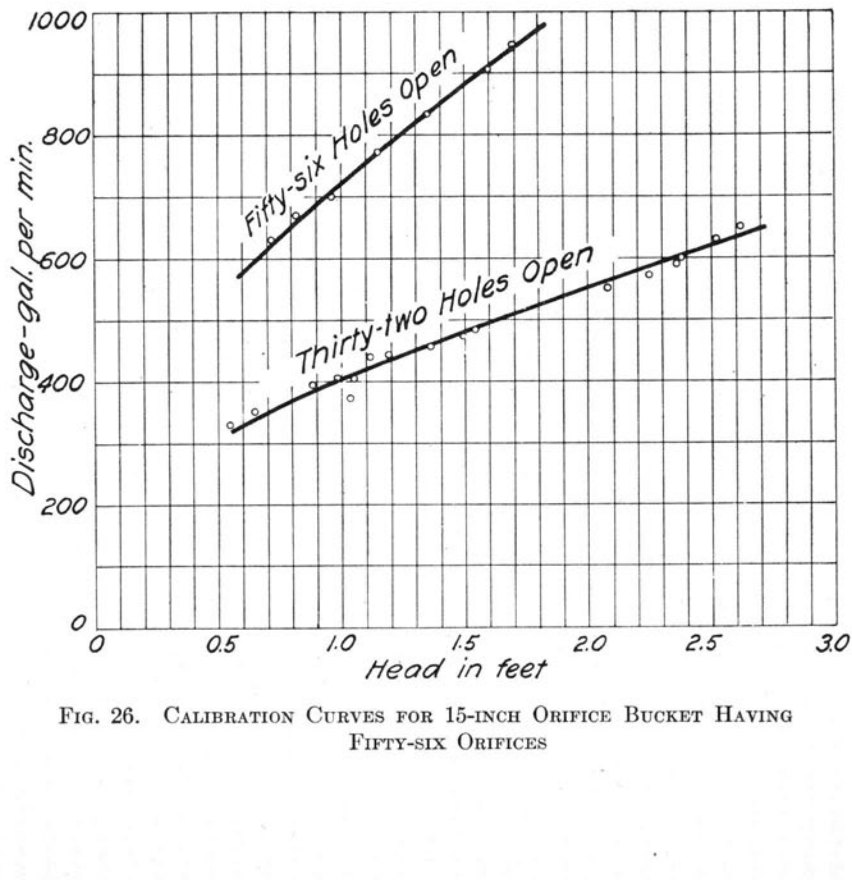

Fig. 26. Calibration Curves for 15-inch Orifice Bucket Having Fifty-six Orifices

3-in. pipe was also tried but did not give satisfactory results, on account of the high velocity which produced an extremely agitated condition of the water in the bucket. This condition may be overcome, however, by use of a deflector or distributor, such as an open bag or sack attached to the end of the discharge pipe.

The rate of discharge for any other number of open orifices for this bucket may be obtained from the equation

$$q=12.8\ n\sqrt{h}$$

which represents fairly well the relation between the quantity, q, in gal. per min., the number of orifices open, n, and the head in the bucket, h, in ft. The experiments give an average coefficient of discharge for the 1-in. orifices of this bucket of about 0.63.

35. *Fifteen-inch Orifice Bucket Having Only Three Orifices.*—Fig. 27 shows an orifice bucket of the same dimensions as the one just described but with three iron tubes about 1 in. long inserted in a 1-in. wooden bottom. It was provided with two screens through which the water passed on its way to the orifices in the bottom of the bucket.

Fig. 27 also shows the calibration curves for this orifice bucket. It will be noted that the discharge ranges from about 35 to 115 gal. per min. This orifice was constructed and calibrated for immediate use and not for experimental purposes. The calibration curves are of value in indicating the reliability of the orifice bucket under a rather wide range in the details of its construction.

36. *Twenty-inch Orifice Bucket Having Nineteen Orifices.*—An illustration of the most elaborate orifice bucket used in the experiments is shown in Fig. 25, the capacity of which is about 1000 gal. per min. It contains a checkerwork of vertical tubes through which the water flows in passing to the orifices. The gage glass which indicates the head on the orifices is connected to a piezometer ring or chamber around the base of the bucket. The pressure of the water in the bucket is transmitted to the piezometer chamber through a large number of ⅛-in. holes. The bottom of the bucket consists of 3/16-in. boiler plate in which nineteen 1⅝-in. circular holes are drilled.

The calibration curves for this orifice bucket are shown in Fig. 28, for all holes open and for ten holes open. The discharge for any other number of orifices open may be found with a fair degree of accuracy from the equation

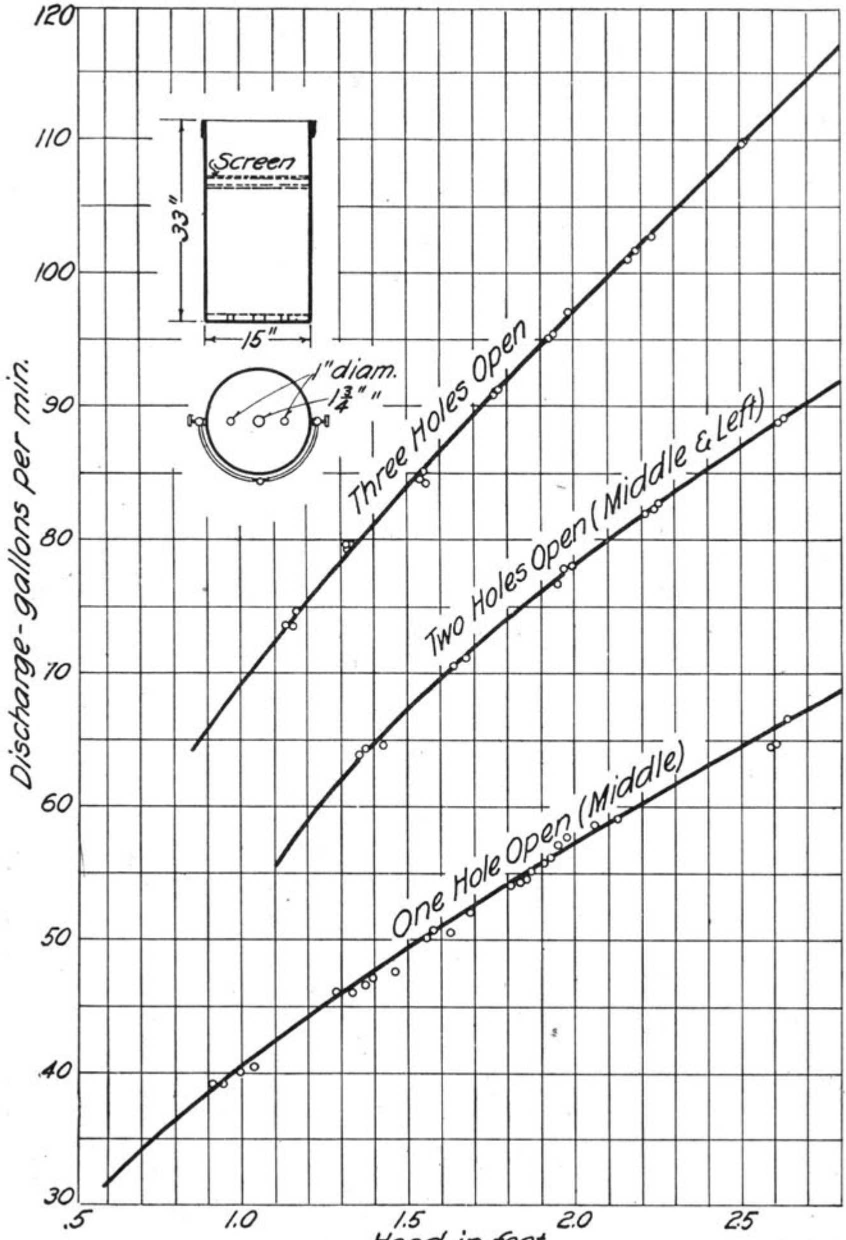

FIG. 27. CALIBRATION CURVES FOR 15-INCH ORIFICE BUCKET HAVING ONLY THREE ORIFICES

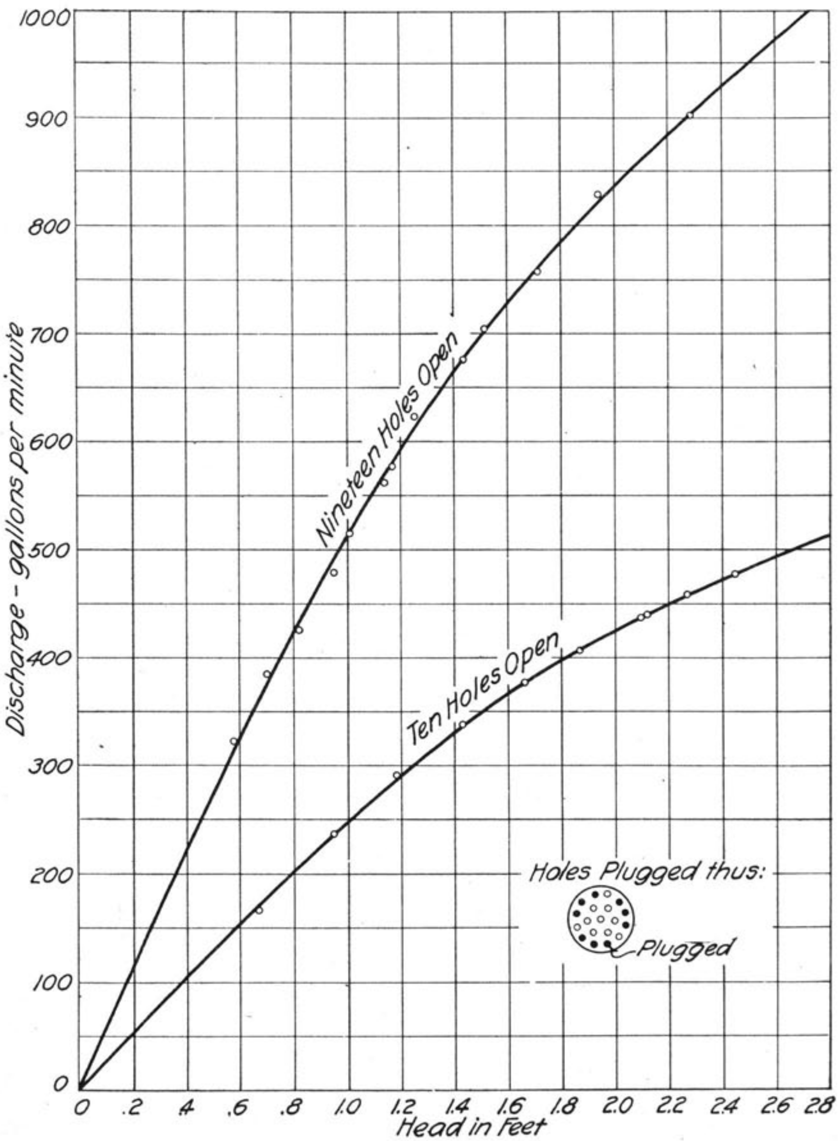

FIG. 28. CALIBRATION CURVES FOR 20-INCH ORIFICE BUCKET HAVING NINETEEN ORIFICES

$$q = 32.7\, n \sqrt{h}$$

in which q is expressed in gal. per min., n is the number of holes open, and h is the head on the orifices in feet. The average coefficient of discharge for the 1⅝-in. orifices of this bucket is 0.61.

The curves in Fig. 28 were obtained when the bucket was supported firmly in an upright position with the stream to be measured discharging vertically in the center of the bucket and with the free fall into the bucket small. The velocity of the inflowing stream, furthermore, was not high (2 or 3 ft. per sec.), thereby causing but little agitation of the water in the bucket. Experiments, however, in which more or less variation from these conditions were allowed indicated that no serious errors resulted.

37. *Conclusions.*—The conditions under which the discharge of water has to be measured are so varied and the purpose or aim in determining the discharge differs so much in different problems that nearly any one of the many common methods of measuring water has a rather restricted field of usefulness, while some methods apply only to very special conditions.

The orifice bucket is designed to meet rather special conditions. It is peculiarly adapted for the measurement of water where a device which is portable (light weight and small size), simple in construction, and low in cost are essential features. The measuring capacity, moreover, covers a considerable range. The orifice bucket is particularly fitted for the measurement of water when the water discharges with considerable blast and momentum from the end of a vertical pipe, in such a manner that the spray covers the entire surface of the water in the bucket, as in the case of air lift pumping. When so used the orifice bucket gives results which should be correct within 5 per cent if the proper precautions are observed in its use, as is shown by the calibration curves, and correct within 10 per cent for the more unfavorable conditions to be met in the field. The highest accuracy is obtained when the orifice bucket is supported rigidly in an upright position with the center of the discharging stream vertically over the center of the bucket. The free fall of the water should be as small as possible and the velocity of the water as it enters the bucket should not be large, unless the stream is distributed, so as to avoid high local velocities in the bucket. The orifice bucket, however, gives very satisfactory results even when there are considerable deviations from these desirable conditions and renders a service for which other measuring devices may not be adapted.

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